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Characterizing Warming through Observed Changes in Temperature Extremes over Himachal Pradesh and Punjab

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Abstract

During the past century, significant temperature changes have taken place and are likely to escalate coupled with human-induced forcings. This projected warming may induce drastic changes in the thermal profile of the region like northwestern India where an increase in mean annual temperature may be causative for monsoon vagaries. This research paper examined the long-term trends in select indices of temperature extremes in parts of north-western India. The results reveal striking facts about the direction and magnitude of change. The cooling of Punjab Plains and warming of mountainous areas of Himachal Pradesh is exhibited by indicators of warm spell duration indicator (WSDI) and cold spell duration indicator (CSDI). These warming rates are most conspicuous in the Middle and the Greater Himalayan regions. An increase in the frequency of warm days (TX90p) and warm nights (TN90p), especially in temperate and cold semi-arid/arid regions of Himachal Pradesh raises serious concerns about imminent water stress, vulnerability and disruption of hydrological balance upon which rests the economic development of the region.

Introduction

Global warming has become a fundamental challenge for humankind as it affects the way we live and govern the resources of this Earth. All anthropogenic activities are affected by climatic variability, which is in turn caused by natural (natural phases of volcanic eruption, El Nino Southern Oscillation etc.) as well as manmade reasons (greenhouse gases production). Global warming is so diverse a concept that it needs a multidisciplinary approach for evaluation and comprehension in terms of its variability in space and time. The indirect effects of global warming can be assessed through periodic measurements of sea-level changes, oceanic warming, incidences of extreme temperatures and intense precipitation. Among all other indicators, evaluation of extreme temperature indices largely provides information regarding the assessment of impacts and projected future implications of global warming. For simplicity an 'extreme event' is something rare within its statistical reference distribution at a particular place (Gray, Scheaffer, and Landsea 1997). IPCC has based its definition on the frequency of occurrence, i.e., an event that is as rare as the 10% or 90% of a particular distribution of an atmospheric variable such as temperature, wind velocity or precipitation (Intergovernmental Panel on Climate Change 2013).

According to the IPCC, *"Widespread changes in extreme temperature have been observed over the last 50 years. Cold days, cold nights and frost have become less frequent, while hot days, hot nights and heatwaves have become more frequent"* (Easterling et al. 2000a; IPCC 2007a). Various studies conducted by meteorologists and climate scientists during past 2 decades concludes that incidences of significantly longer heatwaves have increased and as a result warming has taken place across many regions of world (De and Mukhopadhyay 1998; Kawahara and Yamazaki 1999; Zhai and Pan 2003; Morak, Hegerl, and Christidis 2013; Rohini et al. 2015; Sippel et al. 2016; Mitchell et al. 2016; King and Karoly 2017. Van Oldenborgh et al. (2018) concluded that human activities might enhance the impacts of heatwaves in India while studies conducted by De and Mukhopadhyay (1998) and Lal (2003) validate the increase in the frequency of hot days and multiple-day heatwaves in India.

Temperature extremes will have far-reaching environmental and societal implications. *"There is medium confidence that the observed warming has increased heat-related human mortality and decreased cold-related human mortality in some regions"* (IPCC 2014). Projections for the 21st century by Expert Team for Climate Change Detection and Indices Indicators (ETCCDI) indicated an increase in incidences of hot days and consecutive dry days, indicate warming. There are wide regional variations in the degree of such climatic changes (Brohan et al. 2006); it is likely to cause extreme aridity in some regions (Dai 2013) while others will become wet and hot (Fowler and Wilby 2010). These extremes may induce severe hydrological changes in major river basins such as Ganga and Amazon (Betts et al. 2018); enhancement in vulnerability of small islands, deltas and coastal cities is most likely to happen (Nicholls et al. 2018). Temperature changes are likely to heighten the global environmental risk drastically (Ford and Perace 2010; Ford and Goldhar 2012) and cause serious biodiversity loss (Smith et al. 2018) which may translate into exceedingly negative impacts on key sectors of the economy (Pretis et al. 2018).

In India, extreme temperature events and their impacts are likely to vary spatially due to its large geographical extent and diverse climatic conditions (Sharma 2017). During the past century, the temperature has increased by 0.68°C and warmest daily maximum (TX) temperatures are projected to escalate by 4°C to 5°C with a maximum increase in northern and western India (IPCC, 2013). In regions like Punjab and Himachal Pradesh where sharp spatial temperature gradients exist (Sharma et al. 2018) and regional development and economy is highly dependent on agriculture, horticulture, tourism and hydropower generation, it is all the more important to bringing global level information down to regional and local levels so that potential impacts of climatic changes can be envisioned. This research paper examined trends in temperature extremes with an emphasis on direction and magnitude of change in north-western India over the last 63 years.

Objectives

Following are the research objectives for the present study:

(i) To examine temperature extremes in terms of their location and frequency.

(ii) To analyse the trend of temperature extremes.

Research questions

In accordance with the objectives following research questions were framed:

(i) What have been the trends of temperature extremes in the study area?

(ii) Has the frequency, intensity and location of extreme events changed over time?

The Study Area

Himachal Pradesh and Punjab roughly form a quadrilateral region situated between 29°30′N- 33°12′ north latitudes and 73°55′E-79°04′ east longitudes. The administratively contiguous states have strong physiographic, climatic and hydrological links. The diverse geography of this region is climatically pivotal. The lofty Himalayas protects the region from extremely cold winds from the north while Punjab Plains are vital for determining the arrival of monsoon. 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 and provide fresh water supply through the study area which plays decisive role for development as the key sectors of regional economy, viz. agriculture, horticulture, hydropower, energy systems and tourism are dependent on favourable and stable climatic conditions. It is for these geographical and economic links; the two states have been selected as one unit(Figure 1) to study the thermal regime so as to anticipate the implications of imminent temperature extremes.

Methodology

Data Sources and Types

This study utilized daily gridded temperature data at 1°X1° spatial resolution for the period 1951-2013 acquired from India Meteorological Department (IMD). It examines 4 extreme temperature indices, viz. cold spell duration indicator, warm spell duration indicator, warm nights and warm days. These indicators were grouped into 2 categories of frequency indices and per cent indices (Table 1). The frequency indices measure absolute number of days wherein a particular extreme event occurs over a specified period of time, i.e. days as unit of time. On the other hand, per cent indices calculate the rarity of events in terms of percentage, i.e. per cent of days.

Techniques of Analysis

Since the datasets derived from IMD were already processed using Shephard's interpolation method, it did not have the effect of inhomogeneity. The temperature indices are sensitive to any change in location, exposure, equipment and observation practice; therefore, the datasets were treated for quality control to remove any errors and data inconsistencies using a quality control procedure given by Haylock et al. (2006). For this purpose, the *QC module of 'RclimDex 1.1'* software was used to perform the following procedures:

(i) All missing values were replaced and coded as *-99.9* which is an acceptable format that software recognizes as *'Not Available'* (NA).

(ii) All erroneous values were replaced into NA such as Daily maximum temperature less than daily minimum i.e. Tmax < Tmin.

Methodology given by Zhang et al. (2005) was used to identify the outliers. It was checked for every mean value of daily temperature variable whether or not it falls within the range of *±4 standard deviations* (SD).

Results and Discussion

Frequency Indices

Two major frequency indices, viz. WSDI and CSDI explain temperature behaviour in relative terms, i.e. days. The following significant observations have been recorded about spatial patterns and direction of change:

(a) Cold Spell Duration Indicator (CSDI): CSDI refers to the total annual count of days with at least 6 consecutive days when the minimum temperature remains below the 10th percentile of daily minimum temperature (TN) for that year. Since minimum daily temperatures in a year usually occur during the winters, the value of CSDI indicates the length of a cold spell in the winter season. For mountainous regions, such values are critical for the accumulation of snow in névé and summer ablation.

Trends in CSDI: The study area has received an average CSDI of 8 days/year during 1951-2013, but inter-annual values deviated between 0-43 days/year. There is an overall decrease in CSDI during this period which indicates slight warming of the region as evident from linear and 5-year moving average trend lines (Figure 2). The cold spell duration was low during the 1950s and early 1960s followed by a significant increase till the late 1980s. The magnitude started declining during 1990s and became very low in the post-2000 period. An overall regional decline with significant decrease over 18.18 per cent of the total grids in southwestern and southern Punjab is observed (Figure 3B) while remaining 81.82 per cent grids also show declining but a non-significant trend.

The rate of decrease in CSDI is highest (2.5 to 1.5 days/decade) in the southwestern and southern parts of Punjab (Figure3A). Another prominent zone of diminishing cold spell duration is visible over north-eastern Punjab and adjoining Himachal Pradesh where a decrease of 1.6 to 1.2 days/decade has been recorded. The least change is recorded for entire Himachal Pradesh especially in the southern parts. An overall significant decrease in southwestern and southern Punjab indicates warming of winter temperatures and lesser incidences of longer cold spells. This trend, if persists for long, might affect the length of seasons, particularly during the winters. Another concern relates to the decline of CSDI in temperate and cold semi-arid areas of Himachal Pradesh. Although the change is statistically insignificant, the shortening of cold spell duration might significantly reduce winter snow accumulation and trigger greater summer ablation of snow in higher elevation areas.

(b) Warm Spell Duration Indicator (WSDI)

It refers to the total annual count of days with at least 6 consecutive days when temperature remain above 90th percentile of daily maximum temperature (TX) for that year. It indicates the span of warm spell which in turn determines the length of heatwaves in a region. For mountainous regions, it also determines the summer ablation.

Trends in WSDI

The inter-annual variations in warm spell duration indicator ranged between 0-43 days/year. A slight increase in WSDI value has taken place during 1951-2013 which indicates gradual warming of the region. The trend analysis reveals a cyclic fluctuation during 1950-1990. The lesser WSDI values persisted during mid-1950 and 1960s followed by a small increase during 1970s and a dip during 1980s. The post-1990 period shows an increase in a warm spell in the study area (Fig. 4).

The behaviour of WSDI trends vary spatially but the range is rather narrow. The study area witnessed a uniform pattern of an increasing trend over more than 90.91 per cent of the total grids except for southern and eastern parts of Himachal Pradesh. The trends, however, are statistically non-significant (Figure5B). The most noticeable increase has taken place in the northern Himachal Pradesh over Chamba and Lahaul where WSDI has increased by 2.0-2.7 days/decade (Figure5A).

Increase in warm spell duration is also noticeable over entire Punjab Plains; the extreme southern parts recorded an increase of 1.0-1.4 days/decade while for the western parts of Punjab Plains this increase is 0.7-1.0 days/decade. A large part over Punjab Plains and Himachal Pradesh show a very small rate of positive change in WSDI. Such increase, particularly in the temperate and cold arid zones of Himachal Pradesh point toward the spread of warm spell which may trigger the water scarcity due to higher summer ablation of snow. This may further affect cropping patterns, horticulture productivity and other related economic activities in these areas. There are two zones of negative change, viz. parts of southern Himachal and adjoining Punjab, and eastern parts of the cold semi-arid zone in Himachal Pradesh.

Per cent Indices

This section explains the occurrence, spatial patterns and trends of 2 extreme temperature indices, viz. Warm Nights (percentage of days when TN>90th percentile) and Warm Days (percentage of days when TX>90th percentile).

(a) Warm Nights (Tn90p):

This indicator explains the frequency of nights when daily minimum temperatures exceed the 90th percentile of total annual values. The higher values denote dominance of warmer night-time temperature during peak summers while low values indicate lesser warm nights.

Trends in Tn90p: There is an overall increasing trend in warm nights during 1951-2013. A quick glance at 5-year moving average trend line clearly depicts this change (Figure 6), especially in the post-1990 period. It is quite visible that warming of summer nights has occurred over the entire region. The same can be established by the fact that statistically significant increase is recorded over 54.55 per cent of the total grids (Figure7B) while 45.55 per cent grids shows increasing but a non-significant trend. Such statistically significant increasing trend is most noticeable for southern and central Punjab and southern Himachal Pradesh whereas rest of Punjab Plain and the entire hilly tracts of Himachal Pradesh show a weak increasing trend in Tn90p.

The spatial variations in the rate of change in warm nights (TN10p) are shown in Figure 7A. The highest increasing rate of 1.5 to 2 days/decade is observed for southern Punjab comprising of Fazilka, Ferozepur, Muktsar, Faridkot, Moga, Bathinda, Barnala, Mansa, Sangrur and Fatehgarh Sahib. Over Punjab Plains, the rate of increase diminishes toward the north and become almost nil around Amritsar, Gurdaspur and Pathankot. In Himachal Pradesh, the maximum increase at the rate of 1 day/decade is noticed for southern Himachal Pradesh while eastern parts have recorded an increase of less than a day per decade. The lowest and insignificant increase in warm nights is observed over northern parts of Himachal Pradesh.

(b) Warm Days (Tx90p): It is representative of per cent days when the daily maximum temperature (TX) remains above the 90th percentile of total annual values. It indicates the length of warm spell during peak summers.

Trends in Tx90p

The inter-annual values of TX90p fluctuated from 1.81 to 26.70 per cent during 1951-2013. Despite large inter-annual variations, there has been no significant change in magnitude. Cyclic nature of change is evident; values remained below the long-term average from the mid-1970s to 2000. An increase in TX90p proportion in post 2000 period suggests warming during peak summers. The study area, however, shows a weak increasing trend as evident from the linear trend line (Figure 8). An assortment of both increasing and decreasing trends in the spatial distribution of change in warm days can be seen (Figure 9B). However, no statistically significant change is noticed. The region has experienced a decreasing trend of over 54.55 per cent grids while the rest of the study area shows an increase in the magnitude of warm days. The maximum increasing rate of 0.5-1.0 day/decade can be seen around Chamba and Lahaul in northern Himachal Pradesh. This zone of higher increasing trend gradually merges with Pathankot and Gurdaspur area of Punjab where rate of change is relatively less. The dry semi-arid region of southern and southwestern Punjab also exhibits similar trends (Figure 9A). On the contrary, central and southeastern Punjab shows a decreasing trend. Such negative trends in warm days are more pronounced in southern, central and eastern Himachal Pradesh. The highest decline of 0.8 days/decade is recorded for southern and southeastern Himachal Pradesh.

Discussion

The study area has certainly undergone striking alterations in the pattern and magnitude of extreme temperature indices. The following noteworthy inferences have been drawn:

1) The hilly region of Himachal Pradesh shows comparatively higher rates of summer warming, particularly in the temperate and cold semi-arid regions. The amplification of warm-spell duration indicator further substantiates warming during summers which are very evident in the post-1990 period. The most discernible increase has taken place in the northern Himachal Pradesh. A shift towards overall warming, especially in the post-2000 period, is also evidenced by a shortening of cold-spell duration in winters. The direction of such change is statistically significant over southwestern and southern Punjab. These facts directly point towards warming in the study area, especially in the temperate and cold arid areas of Himachal Pradesh and southwestern Punjab.
2) Furthermore, the warming is also evident from the changing proportions of warm nights and warm days. The two indicate temperature change during peak summer months. Also, day-time temperatures are on the rise even during the winters.
3) Changes in the day and night temperatures during peak summers also confirm warming of the study area. Nights have become visibly warmer and this trend is very conspicuous in the post-1990 period. A statistically significant increase in warm nights is noticeable in southern and central Punjab while hilly tracts of Himachal Pradesh show the least increase in warm-night temperatures. Similarly, the proportion of warm summer days had increased with maximum rise over Chamba and Lahaul area in northern Himachal Pradesh while southern and southeastern Himachal Pradesh shows the highest decline.

Conclusion

To conclude changes in the behaviour of temperature extremes indices are most likely to trigger the issue of water scarcity, availability and occurrence of weather-induced hazards in the study area. Such a predicament may cause serious distress to the regional economy by impacting on cropping patterns, horticulture productivity, tourism, hydropower generation and other related human activities.

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Table – 1: Indicators For Temperature Extremes

ID		Indicator name	Definitions	Unit
Frequency Indices				
1	CSDI	Cold spell Duration Indicator	Annual count with at least 6 consecutive days with TN<10th per centile	days
2	WSDI	Warm Spell Duration Indicator	Annual count with at least 6 consecutive days with TX>90th per centile	days
Per cent Indices				
3	TN90p	Warm Nights	Percentage of days when TN (daily minimum temp.) is >90th per centile	% days
4	TX90p	Warm Days	Percentage of days when TX (daily maximum temp.) is >90th per centile	% days

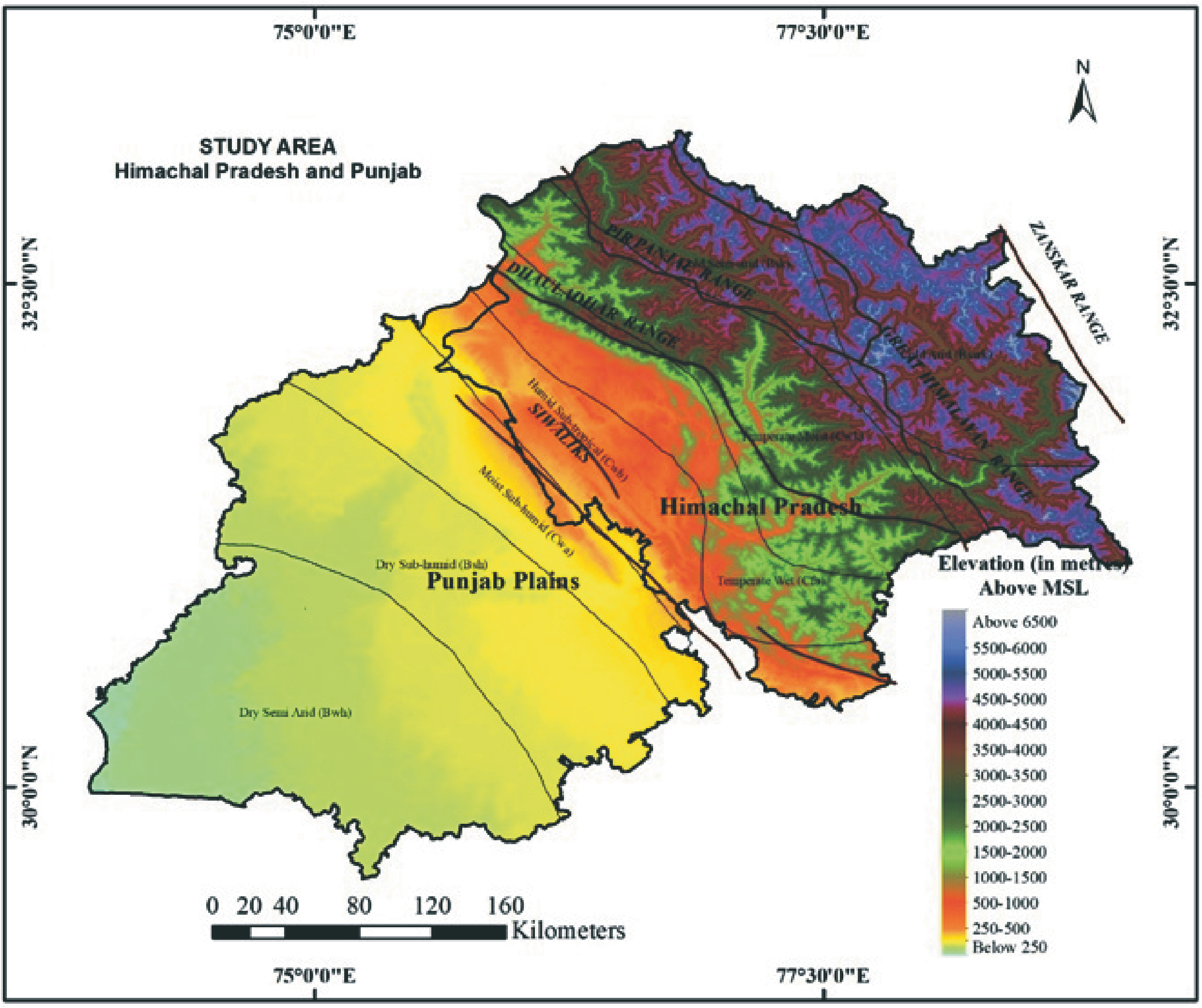

Fig. 1: The Study Area

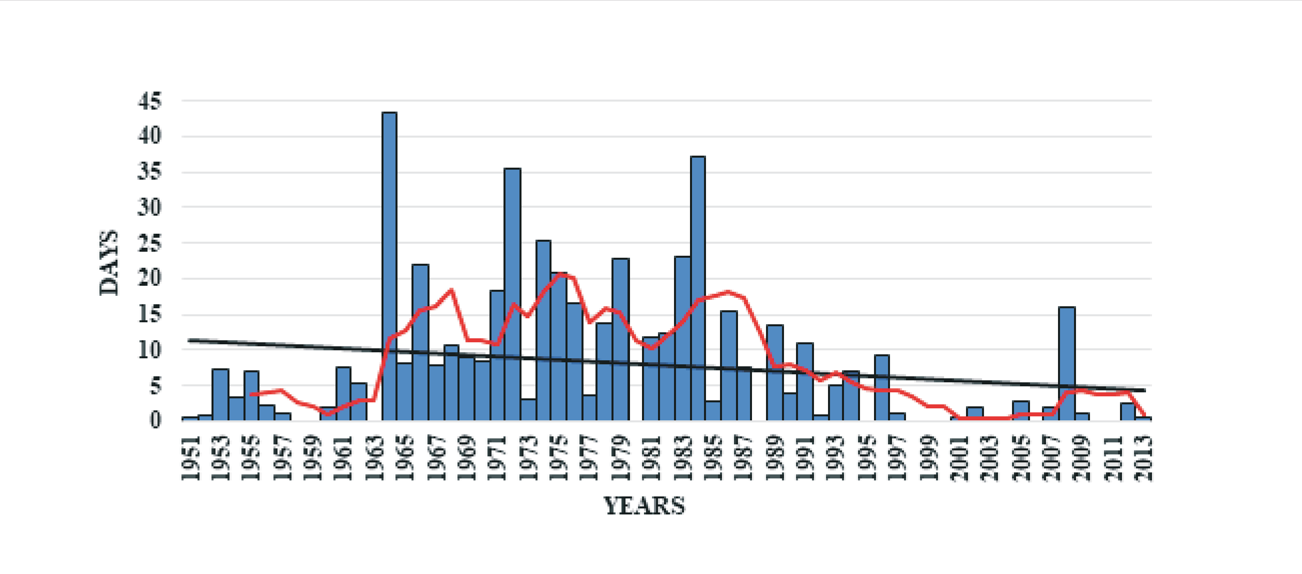

Fig.2: Trends in Cold Spell DurationIndicator (CSDI), 1951 - 2013

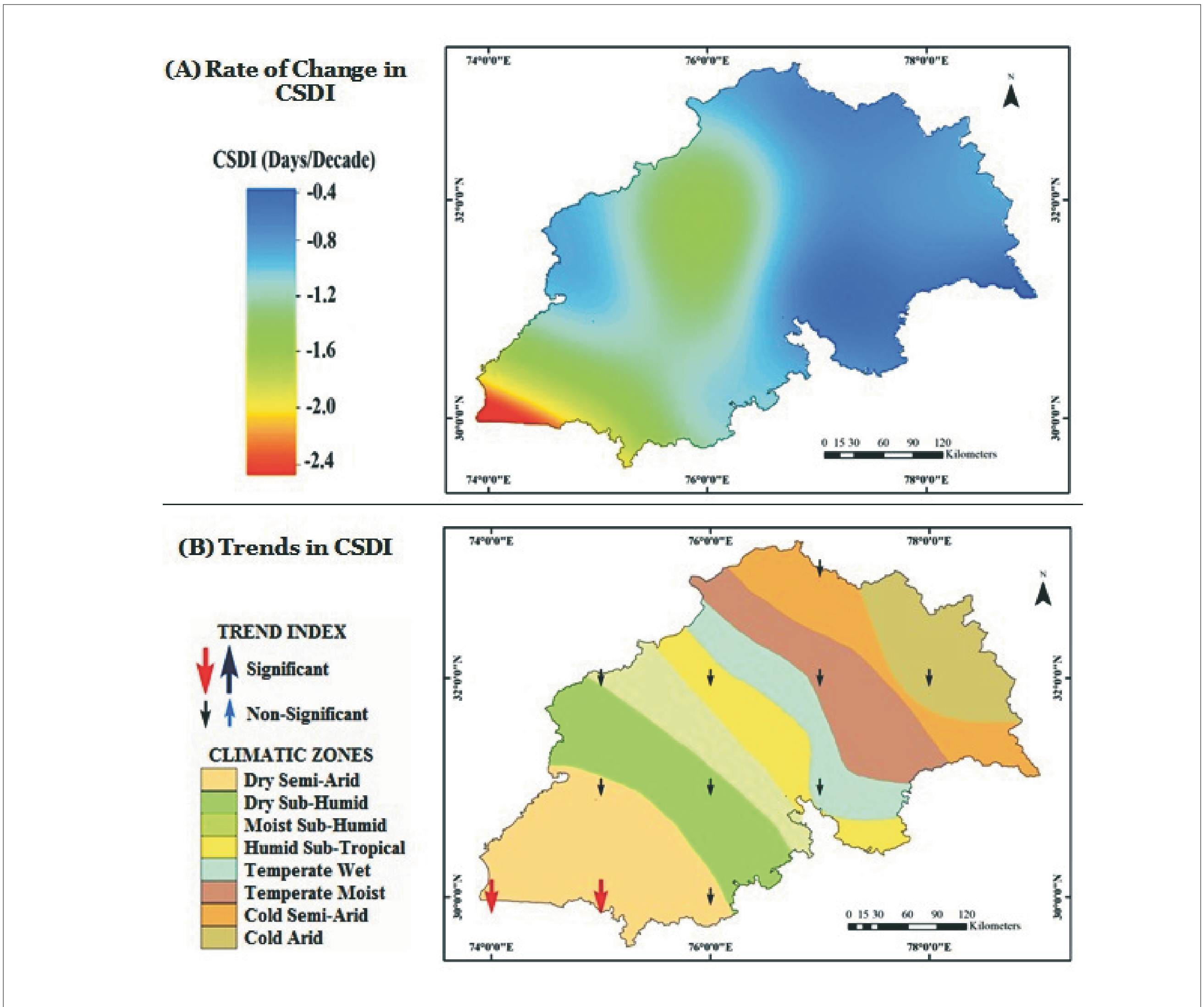

Fig.3: Pattern of the Cold Spell Duration Indicator (CSDI) in the Study Area, 1951 - 2013

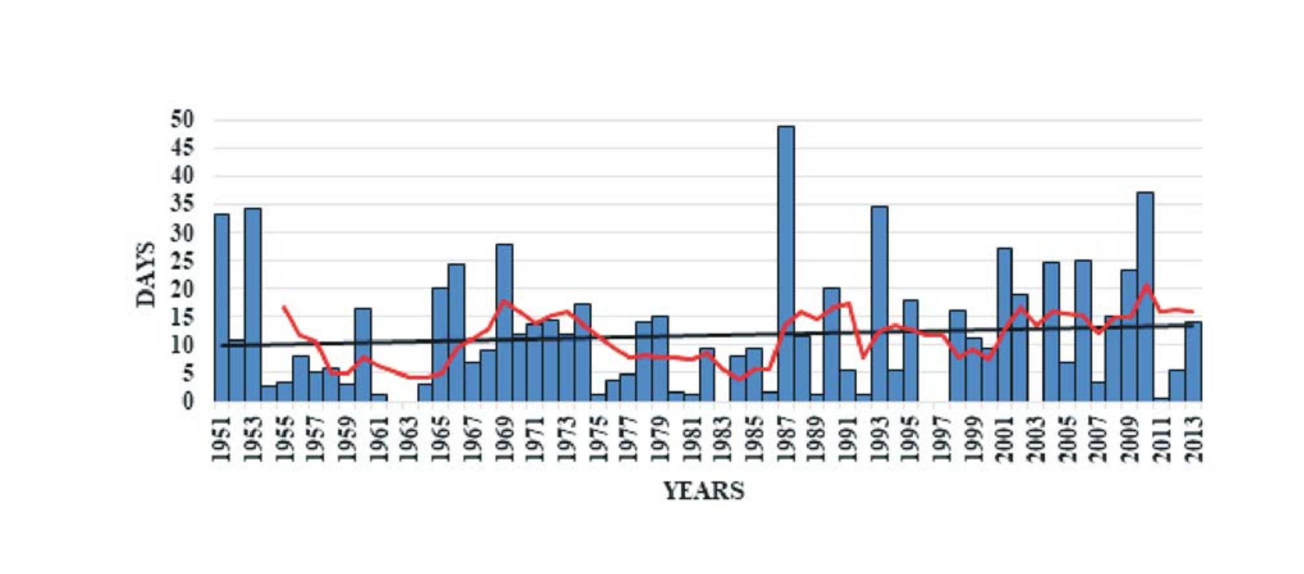

Fig.4: Trends in Warm Spell Duration Indicator (WSDI), 1951 - 2013

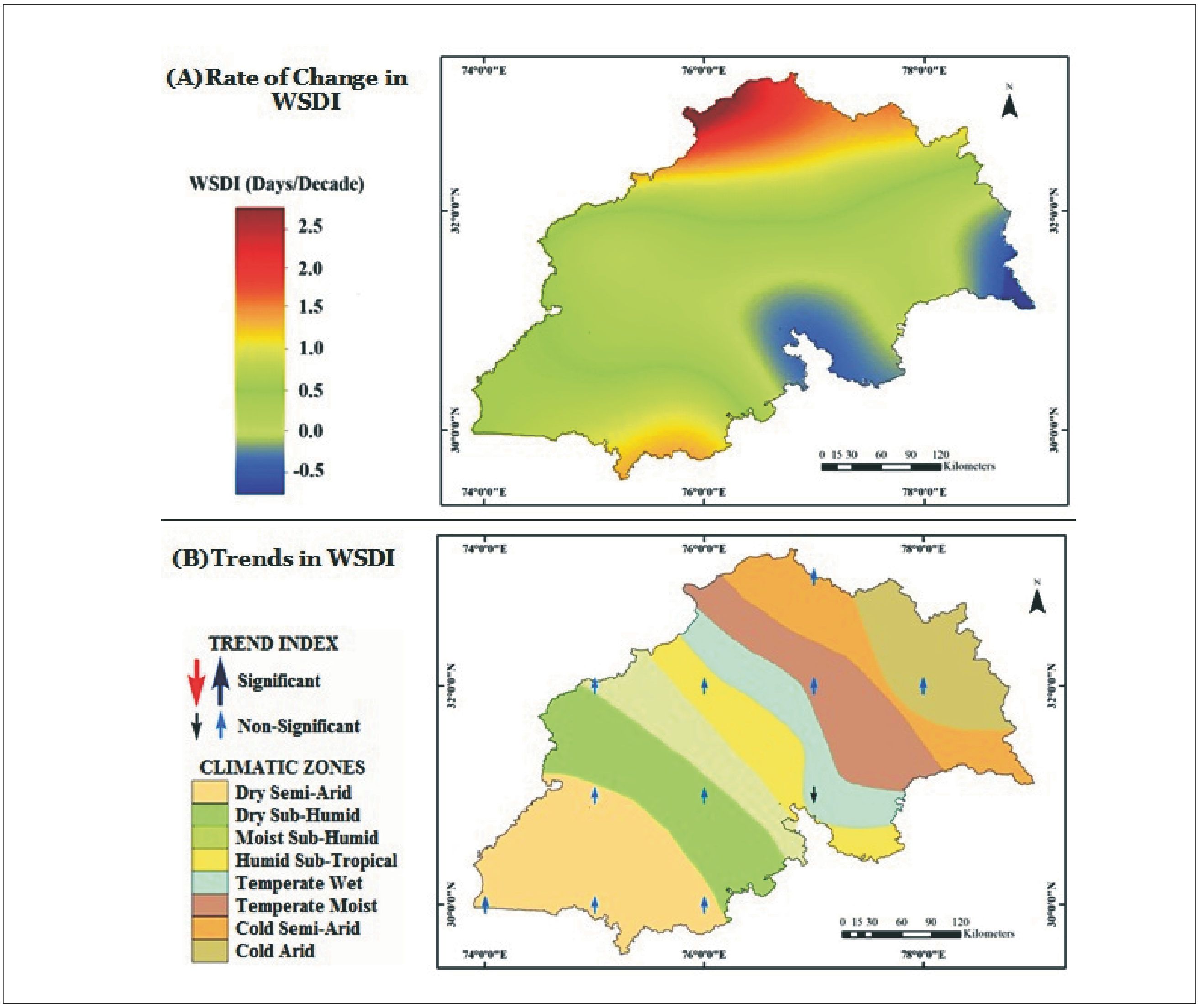

Fig.5: Pattern of the Warm Spell Duration Indicator (CSDI) in the Study Area, 1951 - 2013

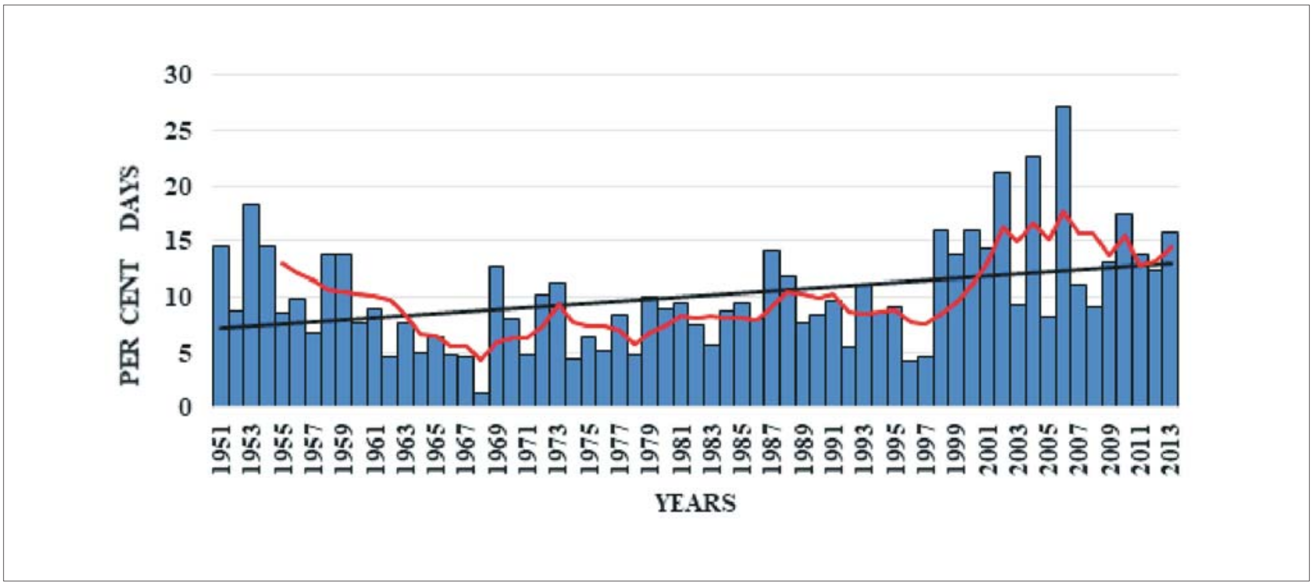

Fig.6: Trends in Warm Nights (TN90p), 1951 - 2013

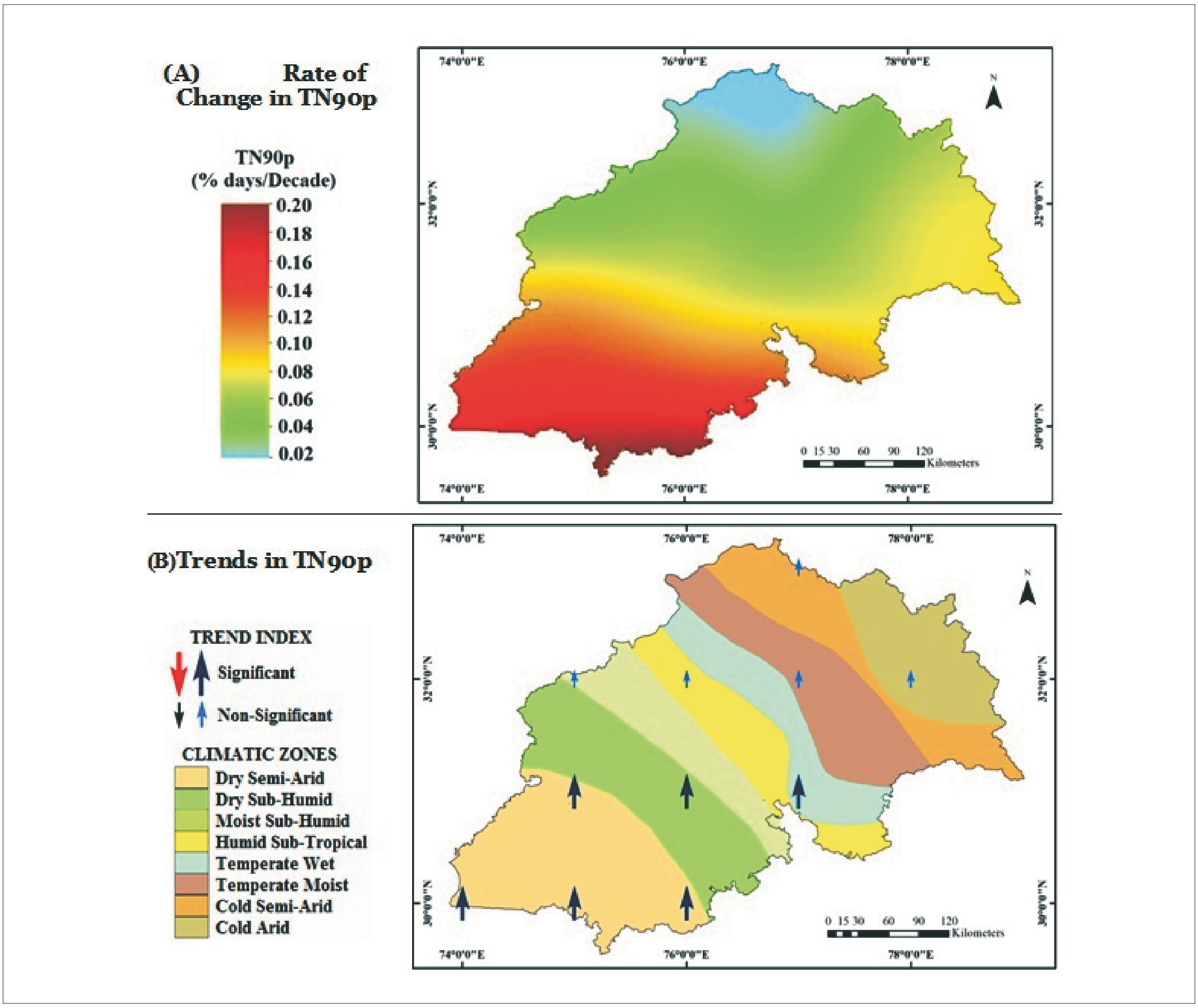

Fig.7: Pattern of the Warm Nights (Tn90p) in the Study Area, 1951 - 2013

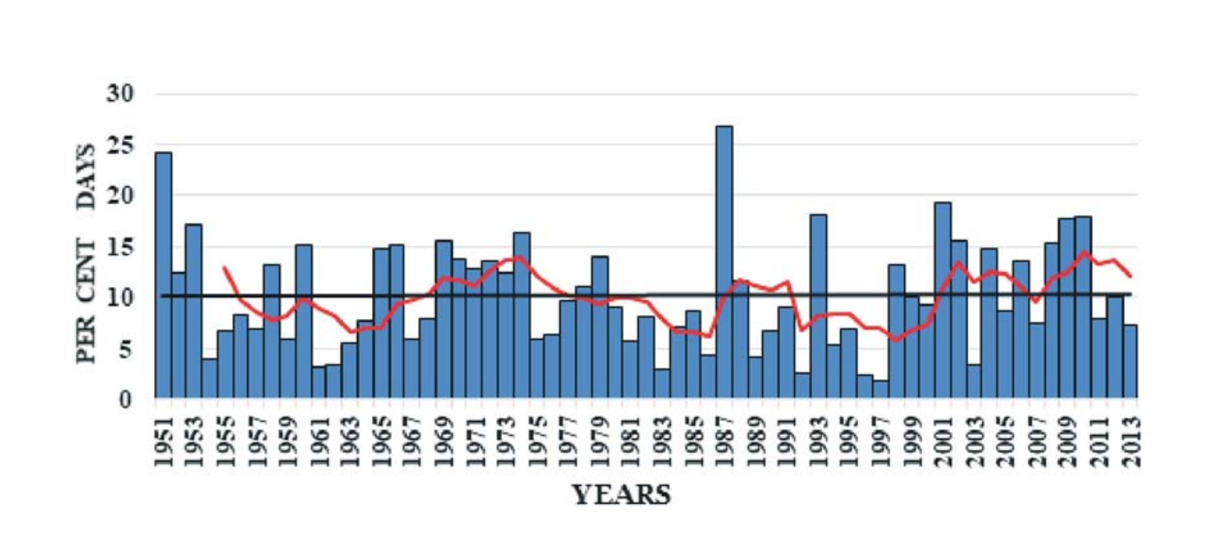

Fig.8: Trends in Warm Days (Tx90p), 1951 - 2013

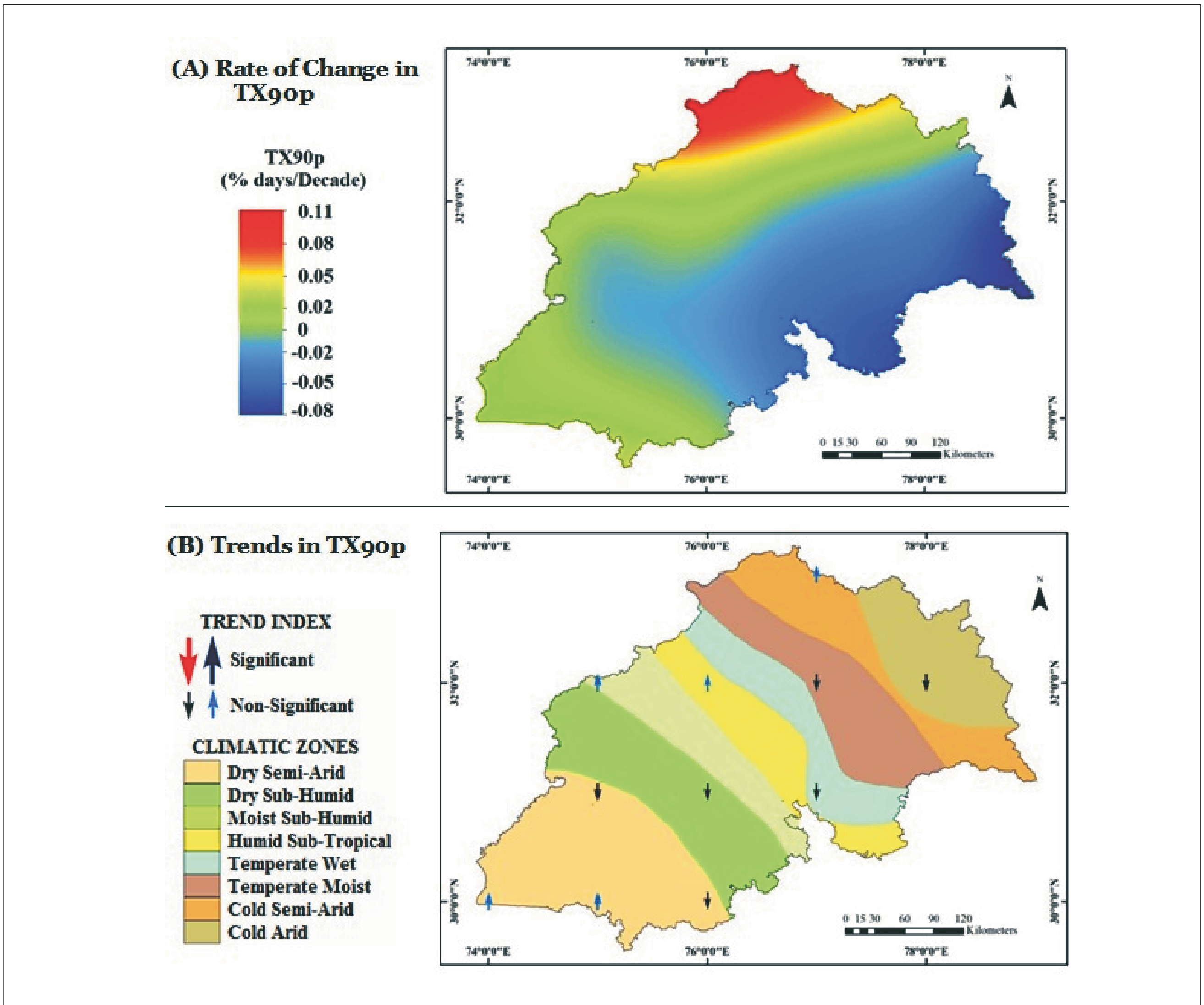

Fig.7: Pattern of the Warm Days (Tx90p) in the Study Area, 1951 - 2013