



# Spatial distribution of unidirectional trends in temperature and temperature extremes in Pakistan

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## Abstract

Pakistan is one of the most vulnerable countries of the world to temperature extremes due to its predominant arid climate and geographic location in the fast temperature rising zone. Spatial distribution of the trends in annual and seasonal temperatures and temperature extremes over Pakistan has been assessed in this study. The gauge-based gridded daily temperature data of Berkeley Earth Surface Temperature (BEST) having a spatial resolution of  $1^\circ \times 1^\circ$  was used for the assessment of trends over the period 1960–2013 using modified Mann-Kendall test (MMK), which can discriminate the multi-decadal oscillatory variations from secular trends. The results show an increase in the annual average of daily maximum and minimum temperatures in 92 and 99% area of Pakistan respectively at 95% level of confidence. The annual temperature is increasing faster in southern high-temperature region compared to other parts of the country. The minimum temperature is rising faster (0.17–0.37 °C/decade) compared to maximum temperature (0.17–0.29 °C/decade) and therefore declination of diurnal temperature range (DTR) (– 0.15 to – 0.08 °C/decade) in some regions. The annual numbers of both hot and cold days are increasing in whole Pakistan except in the northern sub-Himalayan region. Heat waves are on the rise, especially in the hot Sindh plains and the Southern coastal region, while the cold waves are becoming lesser in the northern cold region. Obtained results contradict with the findings of previous studies on temperature trends, which indicate the need for reassessment of climatic trends in Pakistan using the MMK test to understand the anthropogenic impacts of climate change.

## 1 Introduction

The primary effect of rising temperature due to global warming is the increasing frequency and intensity of temperature extremes. A number of studies reported an increase in extreme temperatures in recent years across the globe (Brown et al. 2008; Frías et al. 2012; Alexander 2016; Grotjahn et al. 2016). The major impacts of increasing temperature extremes are frequent heat waves and droughts (Dai 2013; Mohsenipour et al. 2018; Shiru et al. 2018), reduction of agricultural productivity (Asseng et al. 2013), degradation of environmental quality (Naser 2011), depletion of water

resources (Wang et al. 2016b; Salman et al. 2018), and higher risk to human health (Mora et al. 2017). The temperature in the arid region is rising much faster compared to global average temperature rise (IPCC 2014). It has been reported that the regions covering the northern Pakistan and India and western China are among the fastest rising temperature zones of the world (IFAD 2012). The arid and semi-arid regions are more sensitive even to insignificant changes in climatic characteristics due to its fragile ecosystems (Mehrotra and Mehrotra 1995; Samadi et al. 2012; Ahmed et al. 2017b). Such regions are characterized by very complex hydrological systems that often exhibit extreme behaviors, such as extended droughts due to prolonged dry spell and floods due to high-intensity rainfall (Buytaert et al. 2012). The predominantly arid climate and geographical location in the fast temperature rising region have made Pakistan as one of the most vulnerable countries in the world to temperature rise.

Increasing temperature extremes due to global warming are already evident in Pakistan (Revadekar et al. 2012; Sheikh et al. 2015). The highest maximum temperature (53.5 °C) in recent years was recorded in Turbat City of Pakistan on 28 May 2017. Consecutive 5 days with maximum temperature

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above 50 °C is also recorded in recent years in the country. The death toll reached to 1000 due to extreme heat waves in 2017. Projections of climate models revealed continuous increase of temperature extremes in Pakistan due to global warming (Mahmood and Babel 2014; Aslam et al. 2017). As the major part of the country is located in the intense heat zone, the rising temperature would have severe impacts on the economy and livelihood of the people. Knowledge ongoing changes in climate are essential for the development of effective climate change adaptation policies (Wang et al. 2016a; Shahid et al. 2016; Ahmed et al. 2016). Therefore, it is important to understand the spatial pattern in the changes of temperature and temperature extremes of Pakistan.

A number of studies have been conducted to assess the trends in temperature of Pakistan (Islam et al. 2009; Zahid and Rasul 2011; Abbas 2013; Rio et al. 2013; Iqbal et al. 2016; Jahangir et al. 2016; Abbas et al. 2018; Aslam et al. 2017). However, assessment of the trends in temperature extremes is still very limited (Revadekar et al. 2012; Sheikh et al. 2015). Furthermore, no study has been conducted so far to assess the spatial pattern in the trends of temperature and temperature extremes of Pakistan. Studies in neighboring countries revealed a fast increase in a number of temperature extremes in recent years. A review of the studies on temperature and temperature extremes in Pakistan and surrounding regions in neighboring countries bordering Pakistan are given in Table 1.

Most of the previous studies listed in Table 1 used standard Mann-Kendall (MK) trend test over 30–50 years of temperature data, considering that natural variability alters the climate pattern on timescales shorter than 30 years (Shahid 2011). However, a recent analysis of multi-centennial time series data revealed that wet or dry periods exceeding 50 years can exist (Lacombe et al. 2012). The significance of the hydroclimatic trends over time is very sensitive to short-term or long-term persistence in data (Koutsoyiannis 2003). Therefore, consideration of persistence in time series is very important to assess trends in order to understand whether those are due to natural variability or secular change.

Yue and Wang (2002) used “pre-whitening” of the data, where the short-term serial correlation was first removed and then the trend test was performed on the uncorrelated residuals. On the other hand, Hamed and Rao (1998) and Yue and Wang (2004) introduced modified Mann-Kendall trend test to account for the effect of short-term serial correlation. However, none of those methods can handle significant correlation at long lags or the long-term persistence (LTP) in time series (Fathian et al. 2016; Ahmed et al. 2017a). Hamed (2008, 2009) modified the standard MK method to account for the scaling effect, thus enhancing the ability of the test to differentiate the multi-decadal oscillatory variations from LTP. The recent studies revealed that the number of significant trend reduces when modified MK (MMK) test was used (Kumar et al. 2009; Ehsanzadeh and Adamowski 2010;

Lacombe et al. 2012; Shahid et al. 2014; Fathian et al. 2016; Salman et al. 2017a, 2017b; Sa'adi et al. 2017). The finding of the studies cast doubt on the previous results obtained using the MK test. This emphasizes the need for the assessment of temperature trends of Pakistan using the MMK test.

The objectives of this study are to assess the spatial pattern of the trends in (i) annual and seasonal daily average minimum and maximum temperatures; (ii) annual and seasonal diurnal temperature range (DTR); and (iii) a matrix of temperature extremes of Pakistan using MMK tests. The gridded daily data of Berkeley Earth Surface Temperature (BEST) with a spatial resolution of  $1^\circ \times 1^\circ$  for the period 1960–2013 was used for this purpose. A number of studies have been conducted to assess the trends in temperature of Pakistan using the MK test and Sen's slope estimator. A limited number of stations was used in those studies, and therefore, it was not possible to understand the spatial pattern in the trends. Furthermore, the MK test was used in all the previous studies which cannot distinguish the unidirectional trends from the long-term variability of climate. The novelties of the present study are the use of the MMK test to assess the secular trends in temperature of Pakistan and the use of  $1^\circ$  resolution gridded data to reveal the spatial pattern in the trends.

## 2 Study area and data

Pakistan (latitudes  $23^\circ 30' \text{ N}$ – $33^\circ 30' \text{ N}$  and longitudes  $61^\circ \text{ E}$ – $77^\circ \text{ E}$ ) is located in South Asia with an area of 796,095 km<sup>2</sup> (Fig. 1). It has a predominantly arid climate, characterized by hot summer and cool or cold winter. Based on temperature, the climate of Pakistan can be classified into four seasons (Ahmed et al. 2017a): (i) cool and dry winter (December to February), (ii) hot and dry spring (March to May), (iii) rainy monsoon summer (June to August), and (iv) autumn (September to November). However, the onset and duration of seasons vary according to location due to significant spatial and temporal variability of climate over the country. Based on daily maximum and minimum temperatures, the country can be divided into five temperature zones as shown in Fig. 1 (Qasim et al. 2014): (i) zone 1, the Karakoram range in the extreme north with winter minimum and summer maximum average temperatures are  $-6.5$  and  $6.0$  °C respectively; (ii) zone 2, the extended desert in the south west of the country comprising the Makran Belt, the coastal region of Balochistan and the Kharan Desert bordering with Afghanistan having daily average of winter minimum and summer maximum temperatures of  $16.4$  and  $31.4$  °C respectively; (iii) zone 3, the Indus plains in the southeast region of Sindh having average daily winter minimum and summer maximum temperatures of  $20.6$  and  $33.4$  °C respectively; (iv) zone 4, the elevated areas in the central region of Sulaiman range extended from the eastern part of Balochistan to the central and eastern Punjab including the

**Table 1** Summary of the review of recent studies on trends in temperature and temperature extremes in Pakistan and surrounding regions bordering Pakistan

Reference	Country/method	Findings
Iqbal et al. (2016)	Pakistan/MK	Minimum temperature is increasing faster than maximum temperature in Pakistan except in northern region during 1952–2009
Zahid and Rasul (2011)	Pakistan/hypothesis test	The frequency of extreme maximum temperature events is increasing throughout the country during 1965–2009
Abbas (2018)	Sindh, Pakistan/MK	Warm indices had greater trend than cold indices in Sindh Province during 1980–2015
Abbas et al. (2018)	Pakistan/MK	The occurrence of extreme cold nights and days decreased and hot nights and days increased over the period 1981–2010
Rio et al. (2013)	Pakistan/MK	Mean annual temperature of Pakistan increased with pre-monsoon being the most statically significant during 1952–2009
You et al. (2008)	China/Kendall's tau	Extreme cold days and nights decreased, warm days and nights increased, and the DTR decreased during 1961–2005
Zhang et al. (2009)	China/MK test and linear regression (LR)	Minimum temperature is increasing in all the seasons, while maximum temperature only in autumn in the far west of China (near Pakistan) during 1960–2004
You et al. (2011)	China/MK test	Warm days and nights increased, cold days and nights decreased, summer season increased, and DTR decreased during 1961–2003
Fang et al. (2015)	China/MK test	Increase in extreme warm days and decrease in extreme cold nights during 1960–2010 in the southwest China (near Pakistan)
Li et al. (2017)	China/MK test	Significant changes in low and high temperatures in the western region of China (near Pakistan) during 1960–2013
Chen and Zhai (2017)	China/MK test	About one-third of 124 stations of China has experienced significant increases of general hot days during 1961–2015
Wu et al. (2017)	China/MK test	Significant decrease in cold extremes and increase in hot extremes during 1961–2011
Wang et al. (2013)	China/MK test	Increase in the frost days, warm day, warm nights during 1960–2010.
Jaswal et al. (2015)	India/LR	Highest maximum temperature has increased along Pakistan border during 1969–2013
Chakraborty et al. (2017)	India/MK test	All the extreme temperature indices increased along the border of Pakistan during 1969–2005
Panda et al. (2017)	India/MK test	The number of heat waves has increased along the Pakistan border, especially along the border of Sindh Province of Pakistan

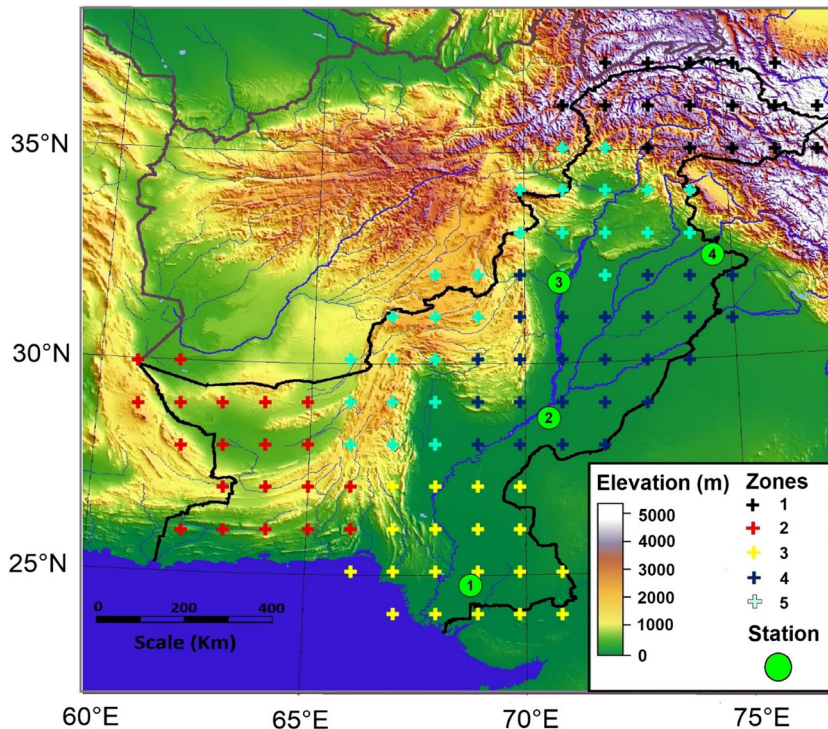
**Table 1** (continued)

Reference	Country/method	Findings
Kothawale et al. (2010)	India/MK test	Increase in pre-monsoon temperature, hot days and nights along the Sindh border, while a decrease in cold nights along the Punjab border
Pingale et al. (2014)	India/MK test	Daily minimum and maximum temperatures are changing along the western border of Rajasthan with Pakistan during 1971–2005
Rahimzadeh et al. (2009)	Iran/MK test	Positive trends in summer days, warm days and tropical nights over a period of 1951 to 1997
Soltani et al. (2016)	Iran/LR	Increasing trend in mean temperature and most of the temperature extremes in Iran in the period of 1975 to 2010
Araghi et al. (2016)	Iran/MK test	A decrease in days of min temp < 30 °C at 67% stations and increase in days of max temp > 30 °C at 40% stations during 1961–2010
Darand et al. (2015)	Iran/MK test	Increasing hot days and nights at 66% and decreasing cold days and nights at 40.9 and 68.5% of Iran respectively during 1962–2004
Taghavi (2010)	Iran/LR	The number of very warm days has increased while the number of very cool days has decreased over the period 1951–2003

Cholistan Desert having average daily winter minimum and summer maximum temperatures of 18.3 and 32.8 °C respectively; and (v) zone 5, the area extends from the Pothohar

Plateau in the central Balochistan to the sub-Himalayan ranges in the extreme north having winter minimum and summer maximum average temperatures of 14.2 and 29.0 °C, respectively.

**Fig. 1** Pakistan in the map of western part of South Asia and the location of BEST grid point over Pakistan. The location of four station data used for the validation of the BEST dataset is also shown on the map. The color of the grid points indicates different climatic zones demarcated based on maximum and minimum temperatures (after Qasim et al. 2014)



Pakistan has 96 meteorological stations distributed over the country. The country has a land area of 796,095 km<sup>2</sup> over which climate and topography vary widely. Therefore, it is very difficult to understand the spatial variability of temperature over the complex topography of Pakistan using a limited number of station data (Ahmed et al. 2014). Gridded data are generally used for the assessment of spatial variability of climate in such region. A large number of gridded datasets have been developed in the last two decades for climatological studies in data scarce regions (Ahmed et al. 2017b). In the present study, daily gauge-based gridded temperature data of BEST having a spatial resolution of 1° × 1° were used for the assessment of spatial distribution of the trends in temperature extremes. The BEST data at 111 grid points covers the whole Pakistan (Fig. 1) for the period 1960–2013 were collected from the website of Berkeley Earth ([berkeleyearth.org](http://berkeleyearth.org)). Gridded land surface temperature (LST) data sets are often limited in length; however, BEST has a comparatively longer period of data which is very important for trend analysis. Furthermore, the BEST data was generated using comparatively more observations than other available Earth surface temperature data products (Wang et al. 2016a). Rahmstorf et al. (2017) assessed temperature trends using different gridded data sets and reported that BEST provides a more linear trend than others. Therefore, the BEST data set was selected for further validation using available observed data and analysis of temperature extremes. Daily maximum and minimum temperature data at 14 gauging locations for the period 1978–2013 were collected from the Pakistan Meteorological Department (PMD). Among them, four station data having the least amount of missing observations were used for the validation of BEST data.

The maps of annual average of daily maximum and minimum temperatures of Pakistan prepared using BEST data for the period 1960–2013 are shown in Fig. 2. The maps show that both the maximum and minimum temperatures are high in zones 3 and 4, while those are lowest in zone 1. The annual average of daily maximum temperature ranges from 0 °C in the north to 32 °C in the southeast, while the daily minimum

temperature ranges from less than –12 °C in the extreme north to 21 °C in the southern coastal regions.

Beside annual and seasonal temperatures and diurnal temperature range, trends in six daily temperature extremes were assessed in this study. Table 2 provides the description of the indices. The indices were calculated on the seasonal or annual basis. Some indices were based on threshold defined as percentiles. The percentiles were calculated from the reference period 1961–1990, which is a climate normal period defined by the World Meteorological Organization.

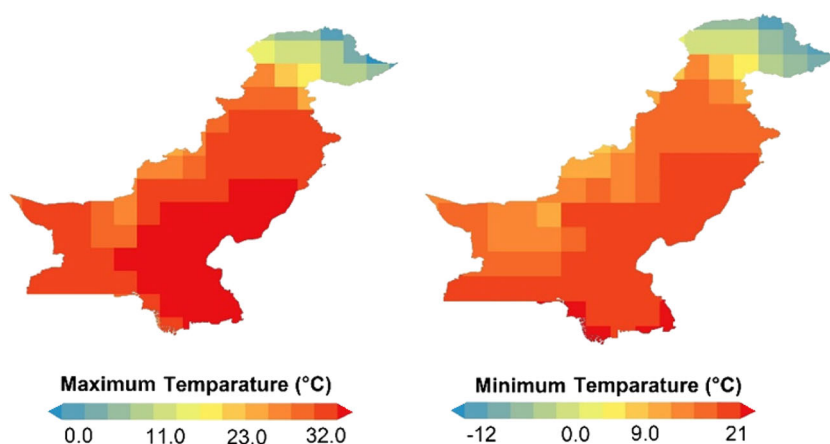
### 3 Methodology

The BEST maximum and minimum temperature data were validated using observed data. Sen's slope method (Sen 1968) was then conducted at each BEST grid point to estimate the rate of change in temperature indices and the MMK trend test (Hamed 2008, 2009) was used to assess the significance of the trend. Besides, Monte Carlo (MC) simulation was used to assess the regional significance of trends in each climatic zone. The magnitude of change in temperature indices and the significance of trend at each BEST grid point were presented using color ramps to show the spatial distribution of trends. The methods are described below.

#### 3.1 Validation of gridded temperature data

The subjective double mass curve method and the objective Student's *t* test were applied to the annual average of daily temperature time series of each observed station to assess homogeneity in data. The double mass curve is a plot of the deviation from a station's accumulated values versus the average accumulation of the climatic zone. Though the stations with high missing data were not selected in this study, they were used for development of double mass curve. The sequential Student's *t* test was conducted to assess homogeneity in data by determining whether various samples are derived from the same population.

**Fig. 2** Spatial distribution of the annual average of daily maximum (left) and minimum (right) temperatures of Pakistan



**Table 2** The definitions of temperature extremes used in this study

Index	Description	Unit
<i>Ex05</i>	Number of days having temperature < 5th percentile of the daily minimum temperature of the base years 1961–1990	Days
<i>Ex95</i>	Number of days having temperature > 95th percentile of the daily maximum temperature of the base years 1961–1990	Days
<i>HW</i>	Number of consecutive days with temperature > 95th percentile of the daily maximum temperature during 1961–1990	Days
<i>CW</i>	Number of consecutive days with temperature < 5th percentile of the daily minimum temperature during 1961–1990	Days
<i>IDMx</i>	Maximum 1-day temperature in a year	°C
<i>IDMn</i>	Minimum 1-day temperature in a year	°C

A matrix of performance index including normalized root-mean-square deviation or error (NRMSE %), percentage bias (PBIAS%), Nash-Sutcliffe efficiency (NSE), modified index of agreement (md), and coefficient of determination ( $R^2$ ) were used for the assessment of performance of the BEST data compared to observed data. The abovementioned performance indices were used as those were found robust to compare the mean, temporal variability, and structural similarity between two sets of data (Ahmed et al. 2017b).

### 3.2 Sen's slope estimator

In Sen's slope estimator (Sen 1968), all the slopes between two consecutive data points in a time series are first measured,

$$Q^l = \frac{x_{i+l} - x_i}{l} \quad (1)$$

where  $Q^l$  is the slope between two data points,  $x_i$  is the measurement at a time  $t$ , and  $x_{i+l}$  is the measurement at a time  $t+l$ . Sen's slope is the median of all the slopes ( $Q^l$ ).

### 3.3 MMK trend tests

In the MMK test (Hamed 2008, 2009), the equivalent normal variates of rank of the de-trended time series are obtained by using the following equation:

$$Z_i = \phi^{-1} \left( \frac{R_i}{n+1} \right) \text{ for } i = 1 : n \quad (2)$$

where  $R_i$  is the rank of the de-trended series  $x_i^l$ ,  $n$  is the length of the time series, and  $\phi^{-1}$  is the inverse standard normal distribution function (mean = 0, standard deviation = 1).

The scaling coefficient or Hurst coefficient,  $H$  is obtained by maximizing log-likelihood function in McLeod and Hipel (1978). This estimate of  $H$  is approximately normally distributed for the uncorrelated case when true  $H$  is 0.5. The correlation matrix for a given Hurst coefficient,  $H$ , is derived by using the following equations:

$$C_n(H) = [\rho_{|j-i|}], \text{ for } i = 1 : n, j = 1 : n \quad (3)$$

$$\rho_l = \frac{1}{2} \left( |l+1|^{2H} - 2|l|^{2H} + |l-1|^{2H} \right) \quad (4)$$

where  $\rho_l$  is the autocorrelation function of lag  $l$  for a given  $H$  and is independent of the time scale of aggregation for the time series (Koutsoyiannis 2003). The value of  $H$  is obtained by maximizing the log-likelihood function of  $H$  as given below:

$$\log L(H) = -\frac{1}{2} \log |C_n(H)| - \frac{Z^T [C_n(H)]^{-1} Z}{2\gamma_o} \quad (5)$$

where  $|C_n(H)|$  is the determinant of correlation matrix  $[C_n(H)]$ ,  $Z^T$  is the transpose vector of equivalent normal variates  $Z$ ,  $[C_n(H)]^{-1}$  is the inverse matrix, and  $\gamma_o$  is the variance of  $z_i$ . Equation (5) can be solved numerically for different values of  $H$ , and the value for which  $\log L(H)$  is maximum is taken as the  $H$  value for the given time series  $x_i$ . In this study, the value of  $H$  is solved between 0.50 and 0.98 with an incremental step of 0.01.

A significance level of  $H$  is determined by using mean ( $\mu_H$ ) and standard deviation ( $\sigma_H$ ) when  $H=0.5$  (normal distribution) as given by the following equations (Hamed 2008):

$$\begin{aligned} \mu_H &= 0.5 - 2.87n^{-0.9067} \\ \sigma_H &= 0.7765n^{-0.5} - 0.0062 \end{aligned} \quad (6)$$

If  $H$  is found to be significant, the variance of  $S$  is calculated by using the following equation for given  $H$ :

$$V(S)^{H'} = \sum_{i < j} \cdot \sum_{k < l} \frac{2}{\pi} \sin^{-1} \left( \frac{\rho|j-i| - \rho|i-l| - \rho|j-k| + \rho|i-k|}{\sqrt{(2-2\rho|i-j|)(2-2\rho|k-l|)}} \right) \quad (7)$$

where  $\rho_l$  is calculated by using Eq. (6) for given  $H$  and  $V(S)^H$  is the biased estimate. The unbiased estimate  $V(S)^H$  is calculated by multiplying by a bias correcting factor  $B$  as below:

$$V(S)^H = V(S)^{H'} \times B \tag{8}$$

where  $B$  is a function of  $H$  as shown below:

$$B = a_0 + a_1H + a_2H^2 + a_3H^3 + a_4H^4 \tag{9}$$

The coefficients  $a_0, a_1, a_2, a_3,$  and  $a_4$  in Eq. (8) are functions of the sample size  $n$ . The values of the coefficients can be found in Hamed (2008). The significance of the MMK test is determined using normalized test statistic  $Z$  as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)^H}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{V(S)^H}} & \text{if } S < 0 \end{cases} \tag{10}$$

A positive or negative value of  $Z$  indicates an upward or downward trend. At 99 and 95% significance levels, the null hypothesis of no trend is rejected if  $|Z| > 2.576$  and 1.96, respectively. Details of the MMK trend test can be found in Hamed (2008).

### 3.4 Monte Carlo simulation for field significance

In MC simulation, the time series data at each station are concurrently shuffled using a random number generator and Sen’s slope is estimated at each station. The total number of stations showing significant at 95% confidence level is counted and denoted as  $N_{mc}^i$ , where the superscript  $i$  denotes the  $i$ th trial and the subscript mc denotes the Monte Carlo experiment. The procedure is repeated for 1000 times. The field is considered to be significant at 95% level of confidence when  $N$  exceeds the 95th percentile of a locally significant trend

from 1000 trials. The MC simulation is widely used for detection of field significance of trends (Chu and Wang 1997; Zhang et al. 2004; Serra et al. 2006; Shahid et al. 2012).

### 3.5 Mapping spatial variability of trends

The magnitude of change in temperature indices estimated using Sen’s slope estimator at all the 111 BEST grid points over Pakistan were presented using color ramps to show the spatial variability in change. The change at each grid point was presented in original resolution of BEST data ( $1^\circ \times 1^\circ$ ) to prepare the map. Symbols “+” or “-” were used to show the significance of trend estimated by MMK test at each grid point.

## 4 Results and discussion

### 4.1 Validation of gridded temperature data

Results of the double mass curves of all the four stations were almost a straight line. This indicates no break point in the time series. The Student’s  $t$  test statistics for the stations were found far below the corresponding test statistics at 0.05 significance level. Therefore, it can be considered that no statistically significant variation or break point exists in any temperature time series.

The homogeneous observed temperature data were used for validation of BEST data. The performance of gridded data was assessed by comparing the observed data with the BEST data at the nearest grid point. Obtained results are presented in Table 3. The NRMSE values were found less than 36.5%, PBIAS less than 1.0%, while NSE, md, and  $R^2$  were found above 0.80 at all the four gauging locations for both maximum and minimum temperature data. The lower values of error and bias and near to 1 values of NSE, md, and  $R^2$  indicate the capability of BEST data in replicating daily maximum and minimum temperatures of Pakistan.

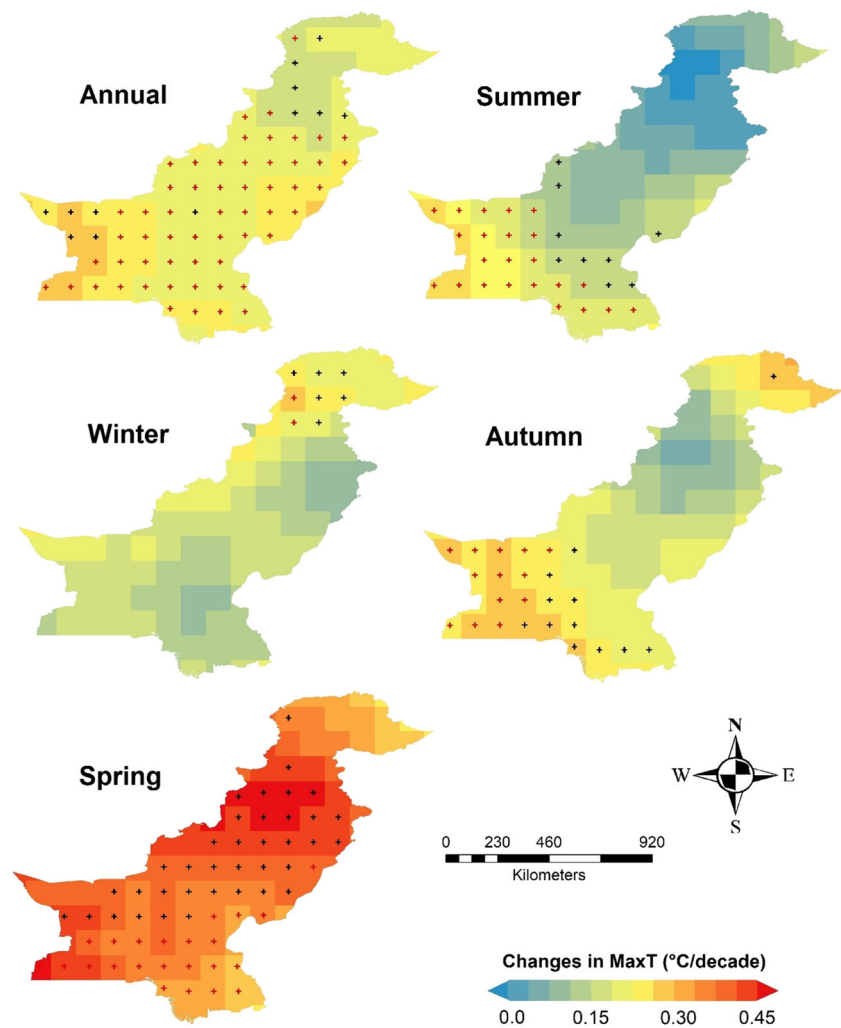
### 4.2 Trends in maximum temperature

Changes in the annual and seasonal averages of daily maximum temperature of Pakistan are shown in Fig. 3. The color

**Table 3** Validation of BEST maximum and minimum temperature data at four stations using a matrix of five performance indices

Performance indices	Badin		Khanpur		D. I Khan		Sialkot	
	Max	Min	Max	Min	Max	Min	Max	Min
NRMSE %	46.0	27.7	30.5	31.4	29.7	22.6	36.5	20.7
PBIAS %	-2.6	1.8	-3.2	-6.6	-4.0	-2.3	-6.2	-1.0
NSE	0.79	0.92	0.91	0.90	0.91	0.95	0.87	0.96
md	0.80	0.88	0.88	0.87	0.87	0.9	0.82	0.92
$R^2$	0.89	0.95	0.94	0.94	0.94	0.95	0.92	0.96

**Fig. 3** Spatial distribution of the trends in the annual and seasonal average of daily maximum temperature. The plus sign in the maps indicates a significant increase in maximum temperature, while the red and black colors of the plus sign indicate the significance of the increase at 99 and 95% levels of confidence respectively



ramp in the maps represents the magnitude of change in temperature obtained using Sen's slope method, while the positive and negative signs represent the significance of trend obtained using the MMK test at each grid point. The black signs refer to the significance of trend at 95% level of confidence, while the red signs refer to the significance of trend at 99% level of confidence.

Figure 3 shows that the annual and seasonal temperatures are increasing over the whole country. The most prominent increases were observed in annual and spring maximum temperatures. The annual average of daily maximum temperature was increasing in whole Pakistan except in zone 1 in the range of 0.17 to 0.29 °C/decade at 95% level of confidence.

The maximum temperature during summer was increasing significantly at 95% level of confidence only in Balochistan (zone 2) and at a few grid points in zones 3 and 5 at a rate of 0.09 to 0.27 °C/decade. The significant increase in winter maximum temperature was found only in zone 1 where the temperatures are usually low. The autumn maximum temperature was increasing mostly in zone 2 in the range of 0.18 to 0.32 °C/decade. The maximum

temperature during autumn was found to increase significantly in the southwestern Makran Coastal Belt and in the southern region of Sindh. The highest increase in maximum temperature among all the seasons was noticed in spring in the range of 0.26 to 0.49 °C/decade. Overall, the results showed significant increase in maximum temperature in zone 2 in all the seasons except in winter.

The rate of change obtained in temperature using Sen's slope estimator is similar to that obtained in previous studies (Qamar-uz-Zaman et al. 2009; Rio et al. 2013; Iqbal et al. 2016; Abbas et al. 2018). However, some of the regions where temperatures were found to change significantly in previous studies were not found significant in the present study. For example, Iqbal (2016) found a significant increase in maximum temperature in northern region Pakistan. However, the present study found a significant increase in daily maximum temperature over whole Pakistan except in the upper northern region. This indicates that some of the temperature trends obtained in previous studies were due the presence of LTP in temperature time series.



The maximum temperature of Pakistan was found to increase faster (0.17–0.29 °C/decade) compared to the global average increase of 0.15 °C/decade. In the western part of Balochistan, the maximum temperature was found to increase two times faster than the global average. Pakistan is a predominantly arid country where skies are mostly clear in almost all over the year (Ahmed et al. 2015). The enhanced downward component of the longwave flux is particularly relevant under clear skies (Vizy et al. 2013; Lelieveld et al. 2016). Therefore, the temperature rises due to enhanced atmospheric greenhouse gases is much higher in Pakistan like many arid regions of the world.

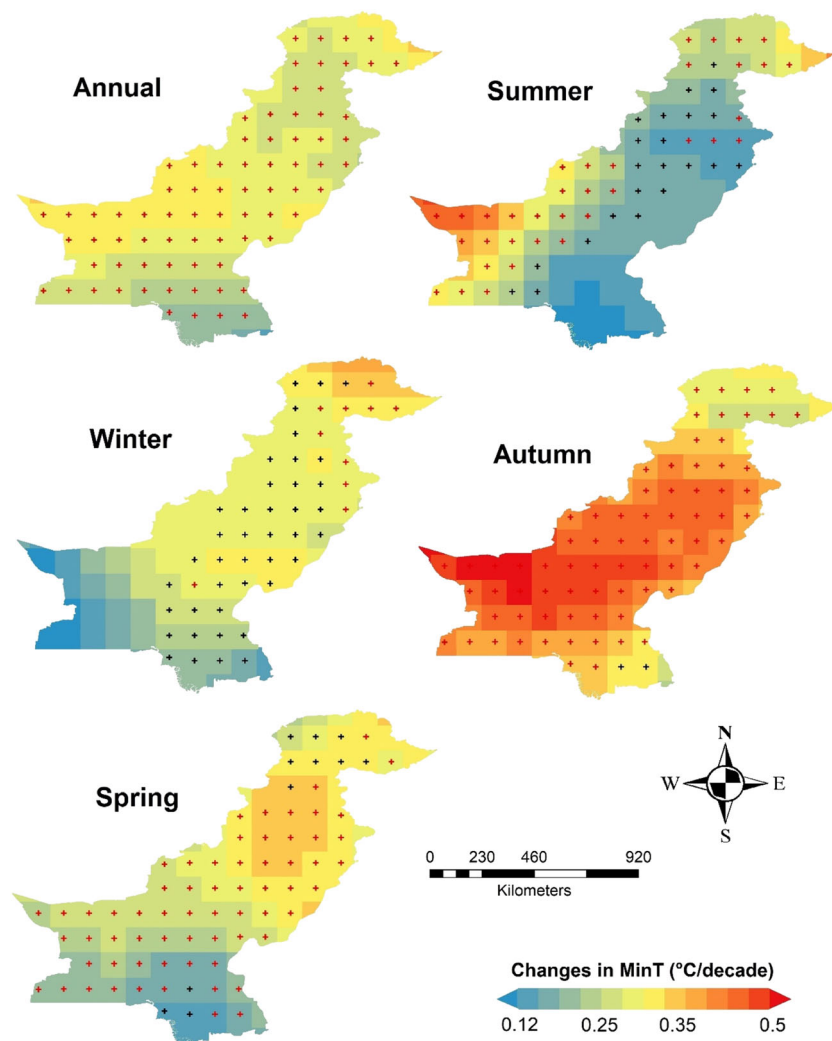
### 4.3 Trends in minimum temperature

Figure 4 shows the changes in the annual and seasonal average of daily minimum temperature over Pakistan. A significant increase in both the annual and the seasonal minimum temperatures was observed in most of the country. The annual average of daily minimum temperature

was found to increase at all the BEST grid points over Pakistan at 99% level of confidence. The fastest increase was found in the northwest of Balochistan desert at a rate of 0.37 °C/decade, while the lowest increase at a rate of 0.17 °C/decade in the coastal plains of Sindh. Among the four seasons, the minimum temperature was found to increase more during autumn (0.26 to 0.52 °C/decade) followed by summer (0.16 to 0.48 °C/decade).

The daily average of summer temperature was increasing in all over Pakistan except in zone 3 and in the southern part of zone 4. The increase was found significant at 99% level of confidence in the western, southwestern, and northern regions of the country. The fastest increase in summer minimum temperature was observed in zone 2 at a rate of 0.48 °C/decade. The winter minimum temperature was increasing in the northern region at 99% level of confidence, while in the other part of the country except in zone 2 at 95% level of confidence. The highest increase was observed in zone 1 at a rate of 0.17 to 0.41 °C/decade. The autumn and spring temperatures

**Fig. 4** Spatial distribution of the trends in the annual and seasonal average of daily minimum temperature. The plus sign in the maps indicates a significant increase in maximum temperature, while the red and black colors of the plus sign indicate the significance of the increase at 99 and 95% levels of confidence, respectively



were increasing in almost all over the country at 99% level of confidence. However, the significant increase in autumn minimum temperature (0.26 to 0.52 °C/decade) was much higher compared to spring minimum temperature (0.16 to 0.37 °C/decade).

#### 4.4 Trends in diurnal temperature range

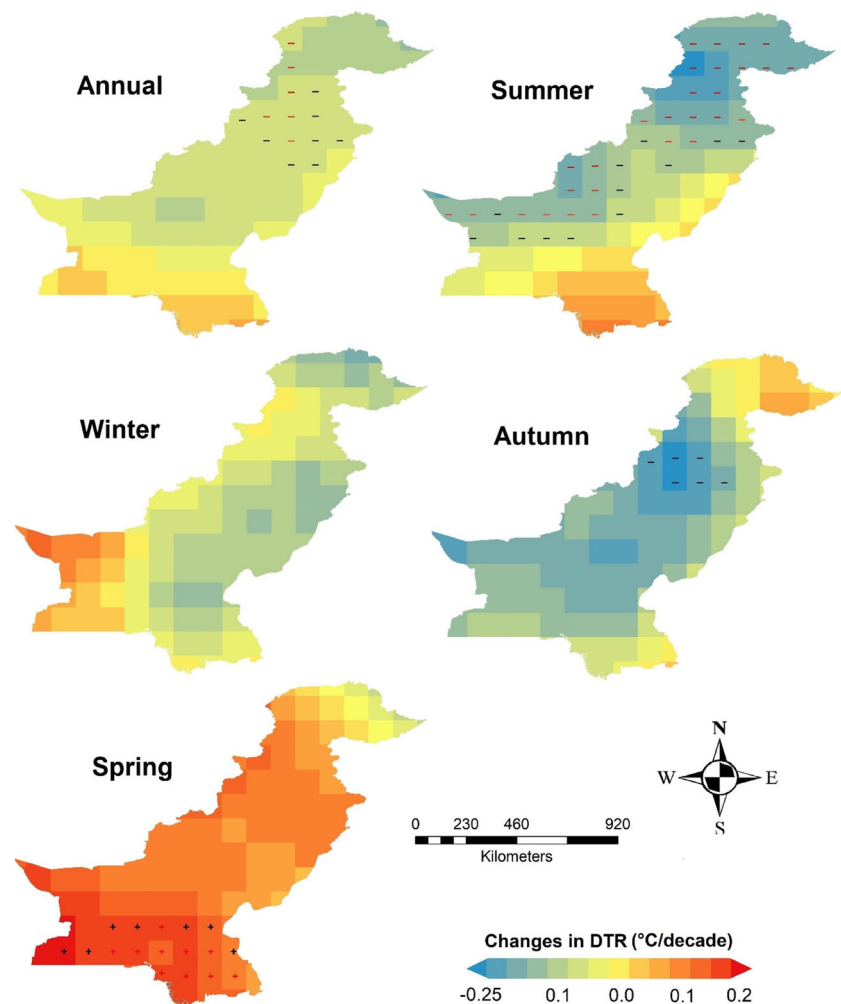
The changes in annual and seasonal DTR are shown in Fig. 5. A decrease in annual, summer, and autumn DTRs in some parts of Pakistan, no change in winter DTR, and an increase in spring DTR in the Southern coastal region were observed. The decrease in annual DTR was found over a small part located in zones 4 and 5 in the range of  $-0.15$  to  $-0.08$  °C/decade. The DTR during summer was noticed to decrease significantly in the northern and western regions. The decrease was observed in the range of  $-0.32$  to  $-0.13$  °C/decade over the zones 1 and 5, and some of the grid points in zone 2 at 95% level of confidence. The autumn DTR was decreasing significantly at 95% level confidence at 6 grid points in a small patch in

the boundary between zones 4 and 5. On the other hand, a significant increase in DTR was observed during spring in the southern coastal region in the range of 0.12 to 0.22 °C/decade.

The higher increase in daily minimum temperatures compared to daily maximum temperature has caused a decrease in DTR of Pakistan up to  $-0.15$  °C/decade. However, the decrease in DTR was found significant only at 19.8% of grid points at 95% level of confidence and 7.2% grid point at 99% level of confidence. DTR is independent of internal climate variations and, therefore, provides additional information for the detection and attribution of climate change in the same manner as spatial fingerprints of climate change (Karoly et al. 2003; Braganza et al. 2003; Shahid et al. 2012). The decrease in annual average of DTR in some parts of Pakistan indicates that impact of global warming induced climate change is already visible in the country.

A decrease in DTR found in the present study collaborates with the findings of the studies conducted in neighboring countries bordering Pakistan. A higher increase in minimum

**Fig. 5** Spatial distribution of the trends in the annual and seasonal average of the diurnal temperature range. The plus/minus sign indicates the significant increase/decrease in DTR, while the red and black colors of the sign indicate the significance of change in DTR at 99 and 95% levels of confidence, respectively



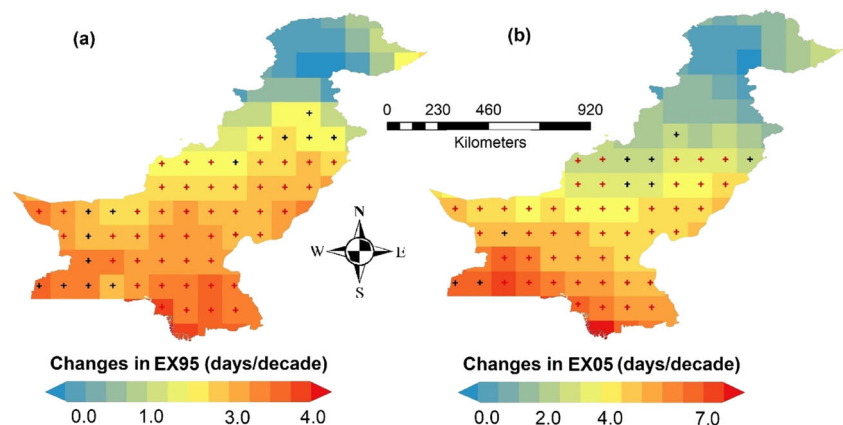
temperature compared to maximum temperature and, therefore, decrease in DTR, have been reported in the regions of China (You et al. 2008; Zhang et al. 2009; You et al. 2011), India (Pingale et al. 2014; Jaswal et al. 2015), and Iran (Araghi et al. 2016; Soltani et al. 2016). You et al. (2011) and You et al. (2008) reported a decrease in DTR at a rate of  $-0.18$  °C/decade in China and  $-0.18$  °C/decade in Tibet Plateau respectively.

#### 4.5 Trends in the number of hot and cold days

The trends in *Ex05* and *Ex95* were assessed to understand the changes in cold nights and hot days (Fig. 6). The *Ex05* was found to increase in most parts of Pakistan except in the upper part of zone 1 (Fig. 6). The highest increase in the number of cold nights (up to 8.12 days/decade) was found in the southern coastal zone at 99% level of significance. The *Ex95* was also found to increase in the regions where cold days were increasing. However, it was found to increase up to 4.41 days/decade at 99% level of confidence in zones 3 and 4, where the daily maximum temperature is the highest in Pakistan.

Despite the increase in annual average of daily minimum temperature, it was found that the extreme cold days were increasing in Pakistan. This contradicts with the findings of the studies conducted in neighboring countries. All the studies in neighboring countries reported a negative trend in days having minimum temperature and a positive trend in days having maximum temperature (Fang et al. 2015; Darand et al. 2015; Chakraborty et al. 2017; Araghi et al. 2016; Wu et al. 2017; Chen and Zhai 2017; Panda et al. 2017). You et al. (2008) and You et al. (2011) reported a decrease in annual number of cold days while an increase in annual number of hot days in the Tibet Plateau and China respectively. Pingale et al. 2014 and Chakraborty et al. (2017) reported a decrease in cold days and nights and an increase in hot days and nights in India. Darand et al. 2015 found an increase in hot days while a decrease in cold nights in Iran.

**Fig. 6** Trends in the annual number of **a** hot days and **b** cold nights compared to the base year (1961–1990). The plus sign indicates a significant increase, while the red and black colors of the sign indicate a significance of the increase at 99 and 95% levels of confidence, respectively



#### 4.6 Trend in heat and cold waves

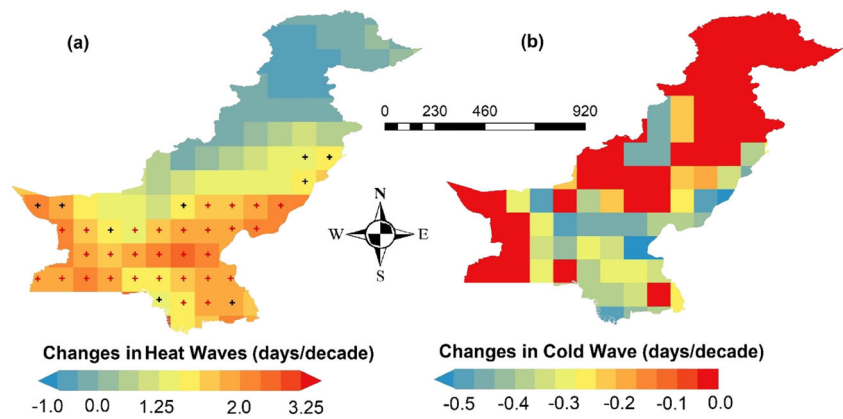
Figure 7 shows the trends in *HW* and *CW* in Pakistan. The *HW* in Pakistan is usually more devastating when it occurs in highly populated areas in zones 3 and 4. The study showed that *HW* was increasing at a rate of 1.11 to 3.33 days/decade in zones 3 and 4. In most of the coastal region, the *HW* was found to increase at 99% level of confidence. On the other hand, the *CW* was found to decrease at 99% level of confidence in zone 1, where the *CW* is very common and at a few grid points in zone 5.

The increase in *HW* is observed mostly in the regions which are often reported to experience heat waves. The major temperature-related concern in Pakistan is the occurrence of heat waves, which often claims lives (Masood et al. 2015). A number of previous studies reported an increase in *HW* in Pakistan (Zahid and Rasul 2011) and the regions in India bordering the Sindh of Pakistan (Panda et al. 2017). The present study revealed that the average annual duration of *HW* in Pakistan was increasing up to 3.33 days/decade. Islam et al. (2009) projected that the *CW* will decrease, and the *HW* will increase over Pakistan in the end of the century. This indicates a more life treating scenario in future due to the continuous increase in temperature due to global warming.

#### 4.7 Trends in 1-day maximum and minimum temperatures

The *IDM<sub>x</sub>* and *IDM<sub>n</sub>* were found to change in the range of 0.08 to 0.21 days/decade and  $-0.14$  to 0.33 days/decade, respectively. However, the significant increase in *IDM<sub>x</sub>* was observed at 8 grid points located in zone 2, while the significant change in *IDM<sub>n</sub>* was observed only at 3 grid points sporadically distributed over Pakistan. Changes in *IDM<sub>x</sub>* and *IDM<sub>n</sub>* were found less in Pakistan compared to neighboring countries.

**Fig. 7** Spatial distribution in the trends of heat waves (a) and cold waves (b) in Pakistan. The plus sign indicates a significant increase, while the red and black colors of the sign indicate the significance of the increase at 99 and 95% levels of confidence, respectively



#### 4.8 Regional trends in temperature and temperature extremes

The regional significance of trends was also assessed for each climatic zone. Field significance of the trend in temperature and temperature extremes in each zone are presented in Table 4. The values in the table show the region change in temperature indices in each climatic zone. The italic represents a significance of regional change at 95% level of confidence, while the boldface indicates a significance of the change at 99% level of confidence. The results revealed an increase in annual maximum and minimum temperatures in all the climatic zones. The higher increase in minimum temperature compared to maximum temperature was observed in all the zones except in zone 4, where both were found to increase at a similar rate. The decrease in annual DTR was found significant only in zone 2. Among the

seasonal temperatures, the minimum temperature was increasing in spring and autumn in all the climatic zones. The least change was observed in winter temperature. The maximum and minimum winter temperatures were found to increase significantly only in zone 2. Both the hot days and cold nights were found to increase in zones 3, 4, and 5. The cold waves were decreasing only in zone 2 and increasing in zone 4. Among the climatic zones, zone 2 was found to be affected more by temperature changes. Both maximum and minimum temperatures for the all the seasons were increasing in this zone. Changes in DTR in all the seasons were also observed in this zone. The temperature extremes were found to affect more in zone 4 compared to other zones. Among the four temperature extremes presented in Table 4, three were found to increase in zone 4. The extreme hot days, cold nights, and heat waves were increasing in this zone.

**Table 4** Regional trends in annual and seasonal temperatures and temperature extremes in all the climatic regions. The number in italic indicates that the regional change is significant at 95% level of confidence, while the number in bold indicates that the change is significant at 99% level of confidence

Index	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Max temperature (°C/decade)	<i>0.021</i>	<i>0.027</i>	<b>0.022</b>	<b>0.023</b>	<i>0.020</i>
Min temperature (°C/decade)	<b>0.032</b>	<i>0.032</i>	<b>0.025</b>	<b>0.023</b>	<b>0.023</b>
DTR (°C/decade)	-0.012	<b>-0.003</b>	-0.002	-0.002	-0.005
Summer max temperature (°C/decade)	0.006	<i>0.022</i>	<i>0.014</i>	0.007	0.003
Summer min temperature (°C/decade)	<b>0.030</b>	<i>0.036</i>	0.015	<i>0.013</i>	<b>0.020</b>
Summer DTR (°C/decade)	<b>-0.022</b>	<b>-0.013</b>	0.001	-0.008	<b>-0.017</b>
Winter max temperature (°C/decade)	0.261	<b>0.001</b>	0.000	0.011	0.013
Winter min temperature (°C/decade)	0.000	<b>0.001</b>	0.000	0.023	0.022
Winter DTR (°C/decade)	0.000	<b>0.001</b>	0.000	-0.012	-0.005
Autumn max temperature (°C/decade)	<i>0.025</i>	<i>0.027</i>	0.025	0.017	0.017
Autumn min temperature (°C/decade)	<i>0.031</i>	<i>0.047</i>	<b>0.037</b>	<b>0.037</b>	<b>0.035</b>
Autumn DTR (°C/decade)	-0.002	<b>-0.017</b>	-0.012	-0.009	-0.011
Spring max temperature (°C/decade)	0.030	<i>0.043</i>	<b>0.034</b>	<i>0.040</i>	<i>0.042</i>
Spring min temperature (°C/decade)	<b>0.032</b>	<i>0.024</i>	<b>0.019</b>	<b>0.024</b>	<i>0.025</i>
Spring DTR (°C/decade)	0.000	<i>0.020</i>	<b>0.016</b>	0.016	0.016
Extreme hot days ( <i>Ex95</i> ) (days/decade)	0.056	0.311	<b>0.355</b>	<b>0.244</b>	<i>0.147</i>
Extreme cold days ( <i>Ex05</i> ) (days/decade)	0.087	0.517	<b>0.568</b>	<b>0.310</b>	<i>0.184</i>
Cold waves (days/decade)	0.000	<b>-0.011</b>	-0.035	0.000	0.000
Heat waves (days/decade)	-0.003	0.210	0.000	<i>0.163</i>	0.029

## 5 Conclusion

Trends in annual and seasonal temperatures and temperature extremes over Pakistan have been assessed in this study. The novelty of the study is the use of the MMK test which allows assessment of unidirectional trends by considering the natural variability of temperature. Furthermore, the maps are prepared to facilitate spatial assessment of trends. The results show an increase in the annual and seasonal average of daily maximum and minimum temperatures at 95% level of confidence in most parts of Pakistan in all the seasons. The minimum temperature is increasing more compared to maximum temperature in most of the seasons. However, the decrease in DTR at 95% level of confidence is visible only in small regions mostly located in the north. Increases in both maximum and minimum temperatures have caused an increase in heat waves and a decrease in cold waves. The heat waves are increasing significantly in high temperature- and heat wave-affected Sindh and Panjab plains of Pakistan, which indicates more deterioration of high temperature-related hazards in the regions. An increase of temperature in the northern sub-Himalayan regions may accelerate glacier melting and increase surface runoff and probability of more floods in the downstream of the rivers flowing through the eastern part of the country.

One of the major aspects of global warming is the increase in temperature and temperature-related extremes. It is very likely that temperature extremes will continue to increase in Pakistan. Therefore, concerted action is very important for Pakistan to build capacity and reduce people's vulnerability to temperature extremes. A major outcome of the study is the production of the maps to show the spatial trends in temperature extremes. The results of the study will be beneficial to improve the understanding of possible changes in temperature hazards. It is expected that the maps and the findings of the study in general will assist in adaptation and mitigation planning to combat the effect of temperature extremes in Pakistan.

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