Analysis of a Historical (1981–2010) Temperature Record of the Punjab Province of Pakistan

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ABSTRACT: Prolonged droughts and uneven monsoons have adversely affected socioeconomic and environmental conditions of Pakistan, especially of the Punjab province. Analysis of historical (1981–2010) daily minimum and maximum temperatures from five cities in semiarid Punjab, Pakistan, was carried out to evaluate spatial and temporal patterns in thermal regimes. A total of 13 climate change indices were calculated using daily minimum and maximum temperatures and analyzed for trend using RClimDex, a program written in the statistical software package R. A nonparametric Mann–Kendall test and Sen's slope estimates were used to determine the statistical significance and magnitude of a trend, respectively. Observed trends in selected indices during 1981–2010 suggest an overall warming in the region. Over the analysis period, the regionally averaged occurrence of extreme cold (10th percentile) nights and days has decreased by −3.94 nights per decade and −0.61 days per decade, respectively. Occurrence of extreme hot (90th percentile) nights and days has increased by 4.19 nights per decade and 0.92 days per decade, respectively. The number of summer days has increased by almost 3 days per decade on average at four out of the five cities. Multan was the only city where the number of summer days has declined by 5 days per decade. Regionally averaged increase in tropical nights was 8.35 nights per decade.

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Regional warming will dictate increased crop water requirements in this semiarid region agriculture, which is already under water-scarce conditions, especially in the Faisalabad district, where saline groundwater is not suitable for crops.

KEYWORDS: Punjab; Pakistan; RClimDex; Regional warming; Semiarid; Temperature indices

1. Introduction

The global average surface temperature has increased by 0.074° ± 0.018°C decade^{-1} over the past century; however, in the past three decades (i.e., since 1981), a higher rate of warming equivalent to 0.177° ± 0.052°C decade^{-1} was calculated (Trenberth et al. 2007). The literature contains miscellaneous reports on historical trend patterns of global/regional warming (Elagib and Mansell 2000; Nasrallah et al. 2004; Safeeq at al. 2012).

Global/regional warming studies depend on time series data of daily minimum and maximum temperatures. Issues regarding quality and availability of daily data and the lack of consistency in methods and periods for analyses make it challenging to compare and interpret the results of studies conducted in different regions of the world (Vincent et al. 2005). This results in reports on mixed trends of global/regional climate patterns in literature. For example, Europe observed symmetric warming of the cold and warm tails of the daily minimum and maximum temperature distributions during the latter half of the twentieth century (Klein-Tank and Konnen 2003). Northern China experienced a decreased frequency of cold days while the number of hot days also decreased in the eastern part of the country during the last four decades of the twentieth century (Zhai et al. 1999). On the other hand, the frequency of warm days and nights increased while the frequency of extreme cool days and nights decreased during the same period (1961–99) in the continent of Australia (Plummer et al. 1999) and in Hawaii during 1969–2007 (Safeeq et al. 2012). During most of the twentieth century (1910–98) the number of frost days decreased over 1910–98, while a small downward trend was also observed in the frequency of days with maximum temperature above the 90th percentile in the United States (Easterling et al. 1997). Southern Canada experienced increasing trends in the 5th and 95th percentiles of the daily minimum and maximum temperature during twentieth century with no consistent trends in extreme hot summer days (Bonsal et al. 2001). Frich et al. (Frich et al. 2002) reported an increase in the number of warm summer nights, a decrease in the annual number of frost days, and a significant increase in the total wet day rainfall from analysis of a global daily station data. For the period of 1961–2000, Vincent et al. (Vincent et al. 2005) calculated significant increasing trends in the percentage of warm nights and decreasing trends in the percentage of cold nights were observed at many stations located closer to the western and eastern coasts of South America. Warming trends were reported by Cheema et al. (Cheema et al. 2006) for the Faisalabad region (Punjab, Pakistan) with an overall increase in temperature by 0.22°C for the analysis period of 1945–2004.

In the recent past, semiarid Pakistan experienced a great variability in temperature resulting into prolonged droughts and uneven monsoon periods leading to adverse flooding (Chaudhary and Rasul 2004; Zahid and Rasul 2011). In the wake of the 2010 and 2011 floods in Pakistan, experts believe that the changing patterns of monsoon are the result of regional warming in South Asia and that the similar events will severely affect the ecosystems in Pakistan in the twenty-first century. Society and infrastructure will become more vulnerable to severe and intense weather. Historically increased surface temperature affects seed germination (Huang et al. 2003; Pérez-Sánchez et al. 2011), plant phenology (Fitter et al. 1995; Sparks et al. 2000; Matsumoto et al. 2003; Gordo and Sanz 2005; Ahas and Aasa 2006; Lu et al. 2006), and evapotranspiration (Le Houérou 1996; Kosa 2011; Rasul et al. 2012). Irrigated landscapes can alter the regional surface energy balance and its associated temperature, humidity, and climate features (Sen Roy et al. 2007). A better understanding of temperature extremes is needed to strategize the resilient resource management for climate change effect mitigation (Vincent et al. 2005). The present study reports on the analysis of temperature trends on 13 of the 27 indices defined by the joint World Meteorological Organization Commission for Climatology (CCL)/Cliimate Variability and Predictability (CLIVAR) Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) using maximum and minimum temperature data collected from the five meteorological stations across semiarid Punjab, Pakistan.

2. Materials and methods

2.1. Study site and data collection

The study site comprises the agriculturally productive major districts of Punjab, Pakistan, including Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi (Figure 1). The cities were selected based on their elevation above mean sea level, geographic locations to represent the agricultural belt of Punjab province, and daily precipitation and temperature thresholds (Table 1). The province of Punjab accommodates over 60% of Pakistan's total population and produces more than 55% of the country's agricultural commodities (Cheema et al. 2012). The selected districts contribute the most toward agricultural production for food and fiber.

Multan is Pakistan's third largest city by area and fifth largest city by population. It is geographic center of the country located at the bank of the Chenab River in south of Punjab and is 562 km away from the country's capital (Islamabad). The topography of its surrounds is flat alluvial plain and is ideal for agriculture, with many citrus and mango farms. It represents the cotton belt of Pakistan. Lands close to the River Chenab are usually flooded in the monsoon season. Multan features an arid climate with very hot summers and mild winters. The city witnesses some of the most extreme weather in the country. The highest recorded temperature is approximately 54°C, and the lowest recorded temperature is approximately −1°C. Dust storms are common occurrences even within the city.

Bahawalnagar is one of the largest cities of Pakistan and is the district capital. It has a very hot and very dry climate in summer, with a maximum temperature reaching 57°C. The climate in winter is very dry and cold with a minimum temperature recorded at 11°C. Bahawalnagar district is usually divided into three parts. These are the riverain area, the canal irrigated plain, and the desert area. The riverain area of the district lies close to the River Satluj. The land in this area is irrigated by nonperennial canals. During the summer monsoons, the area is

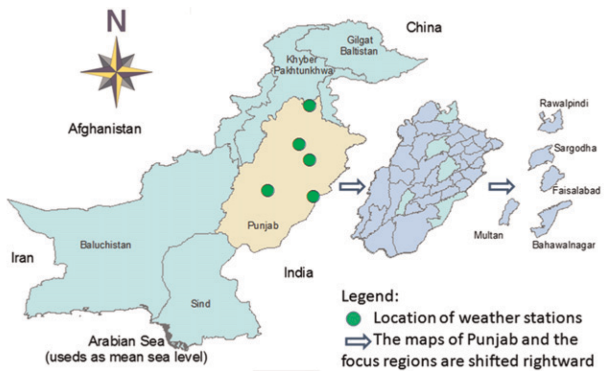

Figure 1. Location of the five selected cities across Punjab: one of the four provinces of Pakistan among Sind, Baluchistan, and Khyber Pakhtunkhwa (KPK).

generally inundated by the river water. The canal irrigated area is a plain; Saddqia Canal irrigates almost the entire district except the Chishtian region and travels near the border of Pakistan and India. The city neighbors the Cholistan Desert that consists of a succession of sand dunes, rising in places to a height of 150 m covered with the vegetation peculiar to the sandy tracts. Bahawalnagar is one of the hottest areas in the country. The main crops of Bahawalnagar are cotton, wheat, and rice.

Faisalabad, formerly known as Lyallpur, is the third largest metropolis in Pakistan and the second largest in the province of Punjab after Lahore. Nicknamed the Manchester of Asia, Faisalabad remains an important industrial city the surrounding countryside of which is irrigated by the lower River Chenab. This area of the city has seen expanded production of cotton, wheat, sugarcane, vegetables, and fruits, which form 55% of Pakistan's exports. Faisalabad stands in the rolling flat plains of Punjab. The River Chenab flows about 30 km northwest while the River Ravi meanders about 40 km southeast of the city. The lower Chenab Canal is the main source of irrigation water, which meets the requirements of 80% of cultivated land. The soil of Faisalabad comprises alluvial deposits mixed with loess having calcareous characteristics, making it very fertile. Because of its high evapotranspiration, Faisalabad features an arid climate. The climate experiences extremes, with a summer maximum temperature of 50°C and a winter temperature of −2°C.

Table 1. List of weather observatories and their attributes.

Stations	Elev (m MSL)	Lat (deg)	Lon (deg)	Daily precipitation (mm)	Upper threshold of daily T_{Max} (°C)	Lower threshold of daily T_{Min} (°C)
Multan	122	30.20	71.43	0.552	31.55	18.58
Bahawalnagar	163	29.95	73.25	0.694	32.62	18.95
Faisalabad	183	31.43	73.10	1.02	31.24	17.46
Sargodha	187	32.05	72.67	1.20	31.61	17.51
Rawalpindi	507	33.62	73.10	3.36	28.86	14.65

Sargodha is, by population, the 11th largest city of Pakistan and 5th largest of the Punjab province. It is located in northeastern Pakistan. For recognition of the best citrus-producing area in the country, it is called the Florida of Pakistan. Sargodha is largely an agricultural and industrial city. Some of the main crops include citrus, wheat, rice, and sugarcane. Over 35 varieties of citrus fruit including oranges (locally known as ''kinnows'') and guavas are grown in the Sargodha district. The River Jhelum flows on its western and northern sides, and the River Chenab lies on its eastern side. The city has a climate of extreme heat and cold. The maximum temperature reaches 50°C in summer while the minimum temperature reaches to the freezing point in winter.

Rawalpindi is the fourth largest city of Pakistan. Geographically, it is located beside Islamabad as its twin city at the bank of Rawal Dam on $\sim$8.8 km^2 artificial reservoir of 58.6 $\times 10^6$ m^3 storage capacity that fulfills the needs of drinking for Rawalpindi and Islamabad urban community and irrigates $\sim$202 ha of agricultural lands surrounding the area of the twin cities. Agriculture in the district is rainfed (barani); wheat, barley, maize, and millet are commonly grown in Rawalpindi district. Similar to neighboring Islamabad, Rawalpindi features a humid subtropical climate with long and very hot summers and wet winters. Rawalpindi, during the summer seasons, experiences a number of thunder- or windstorms; wind speed could reach 168 km h^{-1}, resulting in the collapse of walls and roofs, causing injuries and sometimes death. However, frontal cloud bands also bring quite significant rainfall in the winter. Rawalpindi is chaotic but relatively dust free. The weather is highly variable because of its elevation from mean sea level and location in the piedmonts of the Margala Hills. In summer, the maximum temperature can sometimes soar up to 52°C, while it may drop to a minimum of −4°C in winter.

Daily minimum and maximum temperature data for an analysis period of 30 years (1981–2010) were collected from Pakistan Meteorological Department. Geographical locations (latitude, longitudes, and elevation from mean sea level) of these observatories were determined with a handheld geographical positioning system unit (GPS 72H; Gramin International, Inc., Olathe, Kansas).

2.2. Data quality assessment

RClimDex software (version 1.4) developed at the Climate Research Branch of the Meteorological Service of Canada was used for data quality assessment and calculation of temperature indices. Software was downloaded and the relevant documentation can be accessed from the ETCCDMI website (at http://etccdi.pacificclimate.org/software.shtml). RClimDex was first used for quality control of the data, through automated checking and reporting for erroneous data: for example, anomalies such as missing data, equal minimum and maximum temperatures, or minimum temperature exceeding the same day's maximum temperature.

2.3. Calculation of temperature indices

RClimDex was used to analyze 13 temperature indices concerning semiarid environments (Table 2). The analysis was based on daily maximum temperature,

Table 2. The 13 temperature indices calculated using RClimDex for the selected stations. These indices were jointly established by ETCCDMI and the World Meteorological Organization (WMO) Commission for Climatology (CCL) and the Research Programme CLIVAR.

Indices	Indicator name	Definitions	Units
TN10p	Cool night frequency	Percentage of days with TN < 10th percentile	%
TN90p	Hot night frequency	Percentage of days with TN > 90th percentile	%
TX10p	Cool day frequency	Percentage of days when TX < 10th percentile	%
TX90p	Hot day frequency	Percentage of days when TX > 90th percentile	%
TNn	Minimum T_{Min} (coldest night)	Monthly minimum value of daily minimum temperature	°C
TNx	Maximum T_{Min} (hottest night)	Monthly maximum value of daily minimum temperature	°C
TXn	Minimum T_{Max} (coldest day)	Monthly minimum value of daily temperature	°C
TXx	Maximum T_{Max} (hottest day)	Monthly maximum value of daily maximum temperature	°C
DTR	Diurnal temperature range	Mean of the difference between TX and TN	°C
CSDI	Cold days (cold spell duration indicator)	Annual count of days with at least 6 consecutive days when TN < 10th percentile	Days
WSDI	Warm days (warm spell duration indicator)	Annual count of days with at least 6 consecutive days when TX > 90th percentile	Days
SU25	Summer days	Annual count when TX (daily maximum) > 25°C	Days
TR20	Tropical night	Annual count when TN (daily minimum) > 20°C	Days

daily minimum temperature, and both because the temporal variations of the daytime temperature can be different from those of the nighttime temperature (Vincent et al. 2005). For example, the nighttime temperature over land has increased by about twice the rate of the daytime temperature during the past 50 years (Folland et al. 2001). The selected indices describe warm and cold temperature extremes and were calculated on a monthly and/or annual basis. A few of these indices are based on a fixed threshold (e.g., summer days, tropical nights) and their impacts are easy to understand and to evaluate. Some of them are based on thresholds defined as percentiles (e.g., warm days, cold nights). The temperature indices based on percentiles are calculated as a percentage of days (in a month or year) above or below the 90th or the 10th percentile, respectively. These indices do not represent only the extreme hot days of a summer or the extreme cold nights of a winter but are defined for every day of the calendar year (Jones et al. 1999).

Indices presented in Table 2 can be divided into three groups: the first group includes percentage of time when an index exceeds a percentile limit [i.e., percentage of nights when daily minimum temperature was below the 1981–2010 10th percentile (TN10p), percentage of nights when daily minimum temperature was above 1981–2010 90th percentile (TN90p), percentage of days when daily maximum temperature was below 1981–2010 10th percentile (TX10p), and percentage of days when daily maximum temperature was above 1981–2010 90th percentile (TX90p)], the second group includes indices that measure temperature change (°C) [i.e., temperature of the coldest nights (TNn), temperature of the hottest nights (TNx), temperature of the coldest days (TXn), temperature of the hottest days (TXx), and diurnal temperature range (DTR)], and the third group comprises indices that calculate frequency (number of days) an index exceeds a defined threshold [i.e., cold spell duration indicator (CSDI), warm spell duration indicator (WSDI), summer days when temperature was more than 25°C (SU25), and tropical nights when temperature was more than 20°C (TR20)]. These groups were used to evaluate rare, general, and prevailing climate trends, respectively.

2.4. Descriptive statistics and trend analysis

Descriptive statistics was used to calculate two upper thresholds of daily T_{Max} and T_{Min} data of the past 30 years (1981–2010), collected from Pakistan Meteorological Department site, for the selected cities (Table 1). Lower thresholds of above parameters were set as zero. The ''user defined upper limit of day high'' allows the calculation of the number of days when the daily maximum temperature exceeded this threshold. The ''user defined lower limit of day high'' allows the calculation of the number of days when the daily maximum temperature was below this value. The ''user defined upper limit of day low'' allows calculation of the number of days when the daily minimum temperature exceeded this threshold. The ''user defined lower limit of day low'' allows the calculation of the number of days when the daily minimum temperature was below this limit.

The nonparametric Mann–Kendall test (Mann 1945; Kendall 1955) and Sen's slope estimates (Sen 1968) were used to determine the trends in the selected temperature indices (Table 2). The Mann–Kendall test determines the direction (increasing or decreasing) and statistical significance of a trend and Sen's method determines the magnitude of an existing trend. All the trend analyses were performed over the 30-yr analysis period (1981–2010) using the Excel template application MAKESENS (Salmi et al. 2002). For number of observations > 10, MAKESENS uses Z statistic (normal approximation) for Mann–Kendall test at 90%, 95%, 99%, and 99.9% significance levels. Detailed descriptions of the program can be found in Salmi et al. (Salmi et al. 2002).

3. Results and discussion

Results are presented and discussed in three groups. The first group includes indices (i.e., TN10p, TN90p, TX10p, and TX90p) that calculate percentage of time when an index exceeds a percentile limit depicting rare climate trends. The second group includes indices (i.e., TNn, TNx, TXn, TXx, and DTR) that measure temperature change depicting general climate trends. The third group comprises indices (i.e., CSDI, WSDI, SU25, and TR20) that calculate the frequency (number of days) that an index exceeds a defined threshold depicting prevailing climate trends.

Indices calculations from the daily time series data of temperature extremes revealed statistically significant warming trends during the analysis period 1981–2010 with a high degree of spatial coherence among climate trends of selected cities of Punjab. Slope values of linear trends and their significance indicators derived from Mann–Kendall test and Sen's slope estimates for the trend are given in Table 3.

3.1. Rare climate trends

Rare climate trends are extracted from percentile-based temperature indices that help in determining warming patterns over a certain region based on averaged

Table 3. Slope values and significance levels of linear trends developed on averaged annual anomalies of temperature indices for the selected cities and the analysis period 1981–2010.

Indices	Multan	Bahawalnagar	Faisalabad	Sargodha	Rawalpindi
TN10p	−0.25	−0.32[a]	−0.53[b]	−0.39[c]	−0.54[b]
TN90p	0.29[b]	0.36[b]	0.64[b]	0.44[b]	0.42[b]
TX10p	0.21[a]	−0.21[a]	−0.13	−0.02	−0.20[c]
TX90p	−0.66[b]	0.45[c]	0.48[c]	0.04	0.15
TXn	−0.11[c]	−0.06[a]	−0.07[a]	−0.08[a]	0.01
TXx	−0.06[a]	−0.02	0.03	0.01	0.04[d]
TNn	0.059[a]	0.003	0.058[a]	0.03	−0.01
TNx	−0.02	−0.007	0.059[a]	0.02	0.03[d]
DTR	−0.10[b]	0.01	−0.03[c]	−0.06[b]	−0.04[c]
CSDI	−0.05	−0.24	−0.55[b]	−0.31	−0.22[a]
WSDI	−0.72[c]	0.62[c]	0.45[a]	0.24	0.14
SU25	−0.49	0.63[a]	0.49[d]	0.41	0.52[d]
TR20	0.31	0.86[b]	0.90[b]	0.94[b]	1.30[b]

[a] Significance level $\leq$ 95%.
[b] Significance level $\leq$ 99.9%.
[c] Significance level $\leq$ 99%.
[d] Significance level $\leq$ 90%.

anomalies of annual series of percentage of days that rely on the daily minimum and daily maximum time series data (New et al. 2006).

3.1.1. Cool nights

Figure 2 shows averaged anomalies of annual series of TN10p for selected cities. The cool night frequency index had decreasing trends for all cities and statistically significant trends for all cities except Multan (Table 3 and Figure 2). Linear trends (in percentage of nights) for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were −0.250, −0.323, −0.531, −0.388, and −0.548, respectively. Converting percentages to nights, these correspond to decreasing trends of 2.42, 3.12, 5.13, 3.76, and 5.30 nights per decade. The regionally averaged linear trend (in percentage of nights) was −0.408 for the analysis period. Converting percentage to nights, this corresponds to decreasing trends of 3.94 nights per decade for the selected region. The selected region experienced the most frequent cool nights from 1982 through 1984. Overall, a decreasing trend is apparent for TN10p, indicating that cool nights have significantly decreased in the region from 1981 to 2010.

3.1.2. Hot nights

Figure 3 shows averaged anomalies of annual series TN90p for selected cities. Trends for the hot night frequency index were statistically significant and linearly increasing for all cities (Table 3 and Figure 3). Linear trends (in percentage of nights) for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were 0.298, 0.360, 0.646, 0.436, and 0.427, respectively. Converting percentages to nights, these correspond to increasing trends of 2.88, 3.48, 6.24, 4.22, and 4.13 nights per decade. The regionally averaged linear trend (in percentage of nights) was 0.433

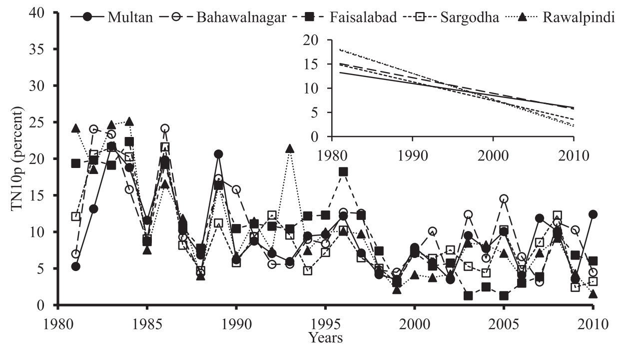

Figure 2. Averaged anomalies of annual TN10p (relative to mean values of minimum temperature for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both panels have similar labels and types, respectively.

for the analysis period. Converting percentage to nights, this corresponds to increasing trends of 4.19 nights per decade. Faisalabad experienced the most frequent hot nights during 2004 and 2006. Overall, an increasing trend is apparent for TN90p, indicating that hot nights have significantly increased across in the selected region from 1981 to 2010.

3.1.3. Cool days

Figure 4 shows averaged anomalies of annual series TX10p for selected cities. Trends for the cool day frequency index were linearly decreasing for all cities except Multan and the same were statistically significant for all cities except Faisalabad and Sargodha (Table 3 and Figure 3). Linear trends (in percentage of

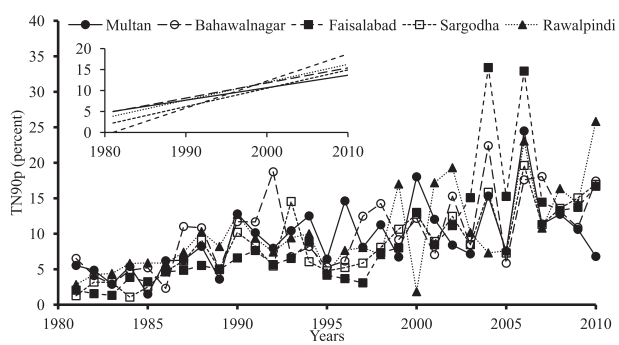

Figure 3. Averaged anomalies of annual TN90p (relative to mean values of minimum temperature for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both panels have similar labels and types, respectively.

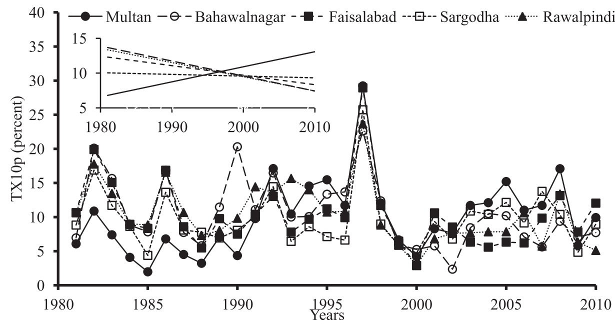

Figure 4. Averaged anomalies of annual TX10p (relative to mean values of maximum temperature for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

days) for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were 0.217, −0.216, −0.137, 0.025, and −0.204, respectively. Converting percentages to days, these correspond to trends of 2.10, −2.09, −1.32, 0.240, and −1.97 nights per decade. The regionally averaged linear trend (in percentage of days) was −0.063 for the analysis period. Converting percentages to days, this corresponds to trends of a smaller number of nights: that is, −0.61 nights per decade due to the effect of increasing trend of Multan. All cities in the province experienced the most frequent cool days during 1997. Overall, a decreasing trend is apparent for TX10p, indicating that cool days have significantly decreased the selected region except in Multan and Faisalabad over the analysis period.

3.1.4. Hot days

Figure 5 shows the averaged anomalies of the annual series of TX90p for selected cities. Trends for hot days frequency index (TX90p) were linearly increasing

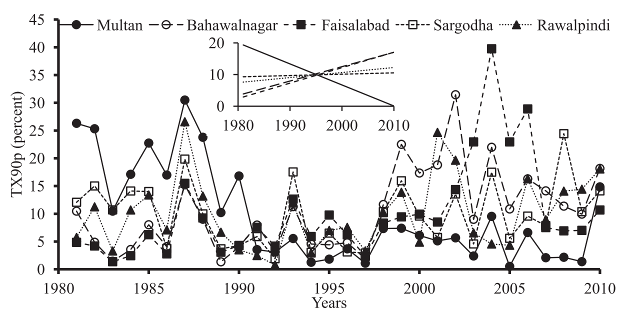

Figure 5. Averaged anomalies of annual TX90p (relative to mean values of maximum temperature for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

for all cities except Multan and the same were statistically significant for all cities except Sargodha and Rawalpindi (Table 3 and Figure 5). Linear trends (in percentage of days) for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were −0.664, 0.453, 0.488, 0.042, and 0.159, respectively. Converting percentages to days, these correspond to trends of −6.42, 4.38, 4.72, 0.41, and 1.54 days per decade. The regionally averaged linear trend (in percentage of days influenced by the dominating negative trend of Multan) was 0.096 for the analysis period. Converting percentage to days, this, influenced by the dominating negative trend of Multan, corresponds to increasing trends of 0.92 days per decade. Faisalabad experienced the most frequent number of hot days in Punjab during 2004 followed by Bahawalnagar and Multan during 2003 and 1987, respectively.

Rare climate trends show an overall decrease (increase) in number of cool nights and cool days (hot nights and hot days) for all cities may be due to real but local urban heat island effects (You et al. 2008). Almost all the selected cities have been expanded because of a population increase in Pakistan during previous decades. Additionally, village people have migrated to urban areas for jobs and education of their children. Because of a shortage of urban transports (rail or buses), the cities in Pakistan have experienced more auto rickshaws, motor bikes, and cars on the road. There is a significant effect of urbanization and land-use change on surface warming at local scale (Kalnay and Cai 2003; Safeeq et al. 2013), though these human-induced changes do not bias surface warming at a global scale (Alley et al. 2007). Cui et al. (Cui et al. 2006) has also reported significant impact of human-induced land-use changes on Tibetan Plateau through a modeling approach. Sen Roy et al. (Sen Roy et al. 2007) determined the impacts of increased irrigation on long-term temperature trends. Through modeling and observational analysis, they found that, during the growing season, irrigation and agricultural activities significantly modulated the surface temperatures over the Indian subcontinent.

Increase of maximum temperature to higher limits (i.e., 40°–50°C) can adversely affect wheat, cotton, or vegetable yield because failure of only one critical enzyme system, in above temperature limits, can cause death of an organism (Abrol and Ingram 1996). Senioniti et al. (Senioniti et al. 1986) established relationships of thermal dependence of enzymes with thermal environment for an organism, which are usually categorized by the three cardinal temperatures: minimum, optimum, and maximum. The thermal dependence of the apparent reaction rate for selected enzymes may indicate the optimal thermal range for a plant (Abrol and Ingram 1996). For crop plants, the thermal kinetic window (TKW; the range over which the apparent Michaelis–Menten constant for CO_2 is minimal and stable) is generally established as a result of thermally induced lipid phase changes, rubisco activity, and the starch synthesis pathway in leaves and reproductive organs (Mahan et al. 1987; Burke 1990). Burke et al. (Burke et al. 1988) reported that, in cotton and wheat, the time during which foliage temperature remains within the TKW was related to dry matter accumulation. The cumulative time during which rainfed crop foliage is outside the TKW provides an index of the degree of extreme temperature stress of the environment that can only be avoided through supplemental or rainfed irrigation (Abrol and Ingram 1996), which is becoming scarce in the region.

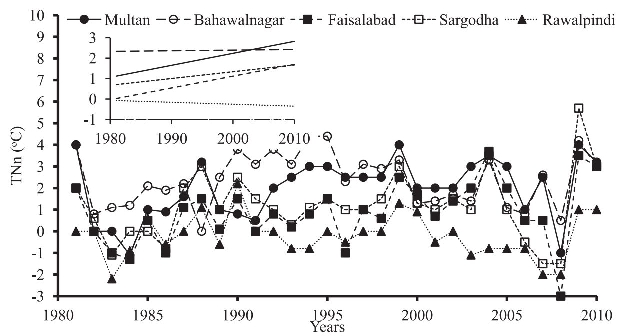

Figure 6. Averaged anomalies of annual TNn (relative to mean values of maximum temperature for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

3.2. General climate trends

General climate trends are extracted from temperature change–based indices that present an evaluation of variations in weather based on day and night temperature. Nighttime variations in temperature extremes are evaluated through TNn (coldest nights) and TNx (hottest nights). Daytime variations in temperature extremes are evaluated through TXn (coldest days) and TXx (hottest days).

3.2.1. Coldest nights

The annual minimum of the daily minimum temperatures (i.e., TNn) for the selected cities and analysis period are shown in Figure 6. Temperatures of the coldest nights had increasing trends for all cities except Rawalpindi and statistically significant patterns for Multan and Faisalabad (Table 3 and Figure 6). Generally, the increasing trends in TNn are compatible with decreasing trends in TN10p because the former index is in absolute temperature units while the latter reports frequency of days below a fixed threshold (New et al. 2006). Trends in Figure 6 concur with literature except for Rawalpindi due to complex nature of its location in the piedmont of the Margala Hills that cause cooling during nights diminished by metropolitan warming effect.

Temperatures of the coldest nights in each year (TNn) showed increasing trends for all cities except Rawalpindi but with fewer statistically significant trends because of the higher variance of this statistic (Table 3). Linear slopes for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were 0.059, 0.003, 0.058, 0.033, and −0.010, respectively, for the analysis period. These slopes correspond to trends of 0.57°, 0.03°, 0.56°, 0.32°, and −0.10°C decade^{-1} for the selected cities, respectively. Regionally averaged slope for TNn is 0.029, which corresponds to trend of 0.28°C decade^{-1}. The lowest averaged annual temperature of the coldest nights of Multan was 0°C in 1983 and below 0°C in 2008. The year 2008 had the highest number and coldest of nights in all cities, whereas the year 2009 had the highest temperatures of the coldest nights for all cities. Sargodha experienced

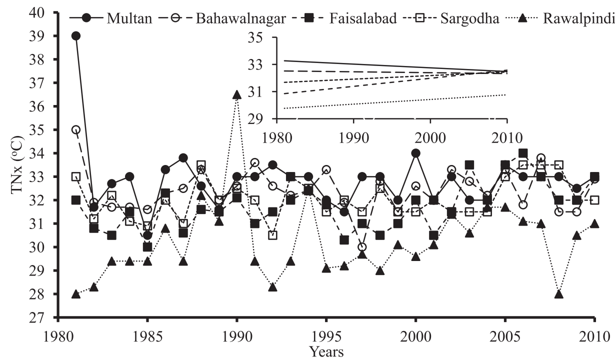

Figure 7. Averaged anomalies of annual TNx (relative to mean values of maximum temperature for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

the highest temperature of the coldest nights (>5°C) during 2009. Rawalpindi experienced the largest number of coldest nights during the analysis period.

3.2.2. Hottest nights

The annual maximum of the daily minimum temperatures (i.e., TNx) for the selected cities and analysis period are shown in Figure 7. Temperatures of the hottest nights had increasing trends for all cities except Multan and Bahawalnagar (Table 3 and Figure 7). There was a statistically significant trend for Faisalabad and Rawalpindi. Linear slopes for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were 0.027, −0.007, 0.059, 0.026, and 0.034, respectively, for the analysis period. These slopes correspond to trends of −0.26°, −0.07°, 0.57°, 0.25°, and 0.33°C decade^{-1} for the selected cities, respectively. Regionally averaged slope for TNx is 0.017, which corresponds to trend of 0.16°C decade^{-1}. The highest averaged annual temperature of the hottest nights among the selected cities was of Multan (39°C) in 1981 followed by those for Rawalpindi (36.5°C) in 1990 and Bahawalnagar (35°C) in 1981. Other than that, Rawalpindi had consistently lower temperatures of the hottest nights among the selected cities and analysis period.

3.2.3. Coldest days

The annual minimum of the daily maximum temperatures (i.e., TXn) for the selected cities and analysis period are shown in Figure 8. Temperatures of the coldest days had decreasing and statistically significant trends for all cities except Rawalpindi (Table 3 and Figure 8). Linear slopes for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were −0.116, −0.069, −0.070, −0.082, and 0.017, respectively, for the analysis period. These slopes correspond to trends of −1.12°, −0.67°, −0.68°, −0.79°, and 0.16°C decade^{-1} for the selected cities, respectively. Regionally averaged slope for TXn is −0.064, which corresponds

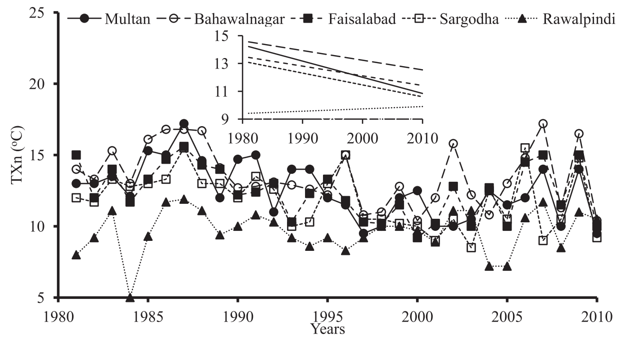

Figure 8. Averaged anomalies of annual TXn (relative to mean values of minimum temperature for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

to a trend of $-0.62°\mathrm{C\,decade}^{-1}$. The lowest averaged annual temperature of the coldest days among the selected cities was 5°C in Rawalpindi in 1984; the city experienced continuous lower temperatures of the coldest days among the selected cities and throughout the analysis period. Among all cities, Multan had the highest temperature (17.5°C) of the coldest days in 1987 followed by Bahawalnagar (17°C) in 1986, 1987, 1988, and 2007.

Other than Rawalpindi, Sargodha—the citrus growing district—had the most number of days when the annual minimum of the daily maximum temperatures (TXn) did not exceed 13°C (a temperature when citrus production is at stake) for all years of the analysis period except 1996, 2006, and 2009. Low temperatures restrict citrus production because of the resultant insufficient heat units despite use of fertilizers and best management practices. Persistently freezing temperatures can damage the fruit and trees as well in severe cold conditions. Low temperatures at mild range (i.e., below 13°C) can have significant limitations for vegetative growth resulting into poor fruit development and quality.

3.2.4. Hottest days

The annual maximum of the daily maximum temperatures (i.e., TXx) for the selected cities and analysis period are shown in Figure 9. Temperatures of the hottest days had increasing trends for all cities except Multan and Bahawalnagar (Table 3 and Figure 9). The trends were statistically significant for Multan and Rawalpindi.

Linear slopes for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were −0.069, −0.025, −0.031, 0.013, and 0.044, respectively, for the analysis period. These slopes correspond to trends of −0.67°, −0.24°, −0.30°, 0.13°, and $0.43°\mathrm{C\,decade}^{-1}$ for the selected cities, respectively. Regionally averaged slope for TXx is −0.014, which corresponds to trend of $-0.13°\mathrm{C\,decade}^{-1}$. The highest averaged annual temperature of the hottest days among the selected cities was recorded for Bahawalnagar and Sargodha during most of the years in the analysis

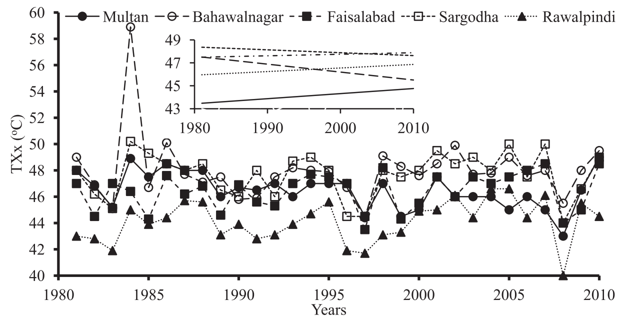

Figure 9. Averaged anomalies of annual TXx (relative to mean values of maximum temperature for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

period. Rawalpindi had consistently the lowest values of TXx throughout the analysis period; the lowest temperature (40°C) was recorded during 2008.

Combinations of high temperature and high humidity in Sargodha district may adversely affect the quality of citrus fruit. Based on a comparison study between coastal and desert-grown citrus fruit in California, Monselise and Turrell (Monselise and Turrell 1959) reported that the peel of fruit developing under the drier climate has a lower water content and is not so tender, presumably because of the hardening effect of moisture stress.

3.2.5. Diurnal temperature range

All the cities showed a statistically significant decrease in DTR except Bahawalnagar (Figure 10). Consequently, the regionally averaged trend is negative (−0.048). Linear slopes for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi

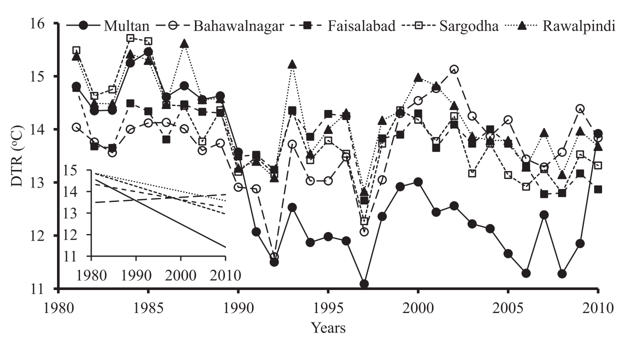

Figure 10. Averaged anomalies of annual diurnal temperature range, i.e., DTR (mean temperature difference of TN and TX) for the 1981–2010 analysis period and selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

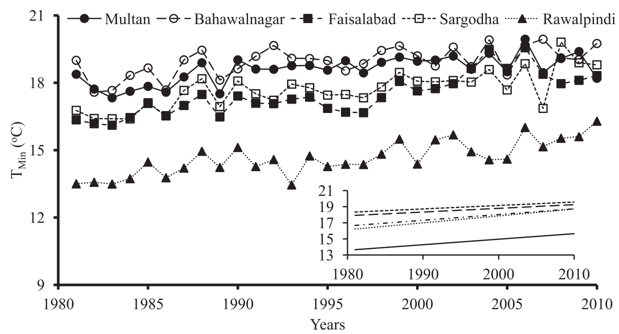

Figure 11. Averaged anomalies of annual T_{Min} (relative to mean values of minimum temperature for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

were −0.108, 0.012, −0.037, −0.064, and −0.044, respectively, for the analysis period. These slopes correspond to trends of −1.04°, 0.12°, −0.36°, −0.62°, and −0.43°C decade^{-1} for the selected cities, respectively. The regionally averaged slope for DTR is −0.048, which corresponds to trend of −0.47°C decade^{-1}.

Trends in DTR (mean temperature difference of T_{Min} and T_{Max}) vary considerably across the province. The decreasing DTR trends across Punjab, Pakistan, are associated with generally steeper trends in minimum temperature indices than maximum temperature indices. The mean temperature difference (DTR) of T_{Min} (Figure 11) and T_{Max} (Figure 12) analysis has shown that T_{Max} remained constant or slightly increased except for Multan, whereas T_{Min} increased faster than T_{Max} for all cities. Urban growth, deforestation, and variations in local land use can all affect the DTR; in particular, urbanized areas often show a narrower DTR than nearby rural areas.

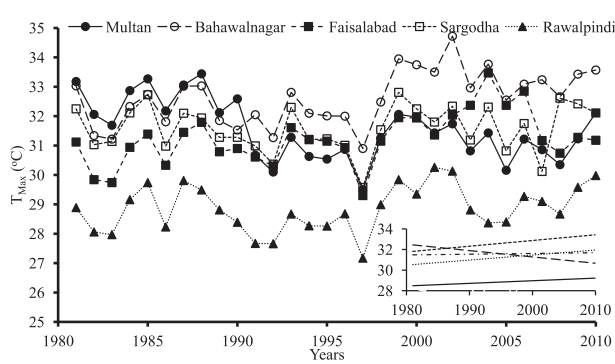

Figure 12. Averaged anomalies of annual T_{Max} (relative to mean values of maximum temperature for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

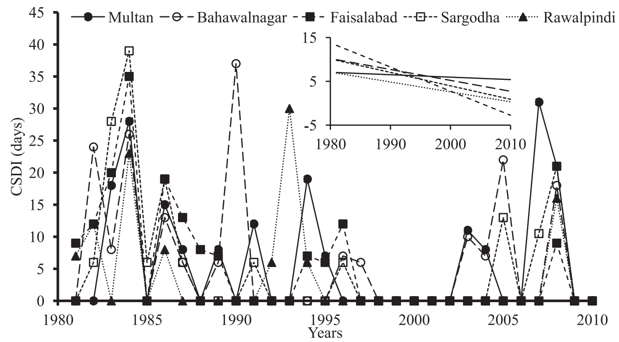

Figure 13. Averaged anomalies of annual CSDI relative to mean (for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

3.3. Prevailing climate trends

This group of indices accounts for frequency (number of days) when an index value exceeds a defined threshold (Table 2) referred to CSDI (cold spells), WSDI (warm spells), SU25 (summer days), and TR20 (tropical nights) Monthly indices are calculated if no more than 3 days are missing in a month, while annual values are calculated if no more than 15 days are missing in a year. No annual value is calculated if any one month's data are missing. For threshold indices, a threshold was calculated if at least 70% of data are present. For WSDI and CSDI, a spell can continue into the next year and is counted against the year in which the spell ends; for example, a cold spell (CSDI) in the Northern Hemisphere beginning on 31 December 2000 and ending on 6 January 2001 is counted toward the total number of cold spells in 2001.

3.3.1. Cold spells

Cold spell duration (computed from CSDI) decreased for all cities over the analysis period (Figure 13). The calculated decrease was statistically significant for Faisalabad and Rawalpindi only (Table 3). Regionally averaged rate of decrease in CSDI was −0.278, resulting from −0.056, −0.249, −0.550, −0.307, and −0.227 for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi, respectively. Converting the decreasing rate in CSDI to the number of occurrence of CSDI per decade: this corresponds to 0.54, 2.41, 5.32, 2.97, and 2.19 days per decade for the above cities, respectively. Regionally averaged occurrences were calculated to be 2.69 days per decade. All the cities experienced the most number of cold spells during 1984 (Figure 13). Maximum CSDI for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were recorded during 2007 (30 days), 1990 (37 days), 1984 (35 days), 1984 (39 days), and 1993 (30 days), respectively.

3.3.2. Warm spells

Warm spell duration (computed from WSDI) increased for all cities except for Multan (Figure 14). The increasing trends were statistically significant for

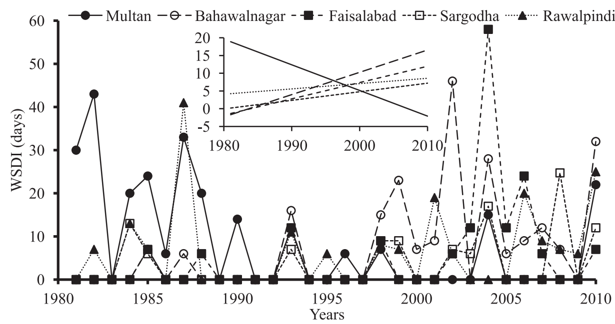

Figure 14. Averaged anomalies of annual WSDI relative to mean (for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

Bahawalnagar and Faisalabad only (Table 3). The trend for Multan was statistically significant and consistently decreasing reflecting a trend of stability in the weather of Multan. Regionally averaged rate of decrease in WSDI was 0.151 resulting from −0.723, 0.629, 0.459, 0.241, and 0.150 for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi, respectively. Converting the above rates of WSDI to a number of occurrences per decade corresponds to −6.99, 6.08, 4.44, 2.33, and 1.45 for above cities, respectively. Regionally averaged occurrences were computed to be 1.46 days per decade. Excluding Multan from the calculations, regionally averaged occurrences are computed to be 3.57 days per decade. Maximum WSDI for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were recorded during 1982 (42 days), 2002 (43 days), 2004 (59 days), 2008 (20 days), and 1987 (40 days), respectively.

3.3.3. Summer days

Summer days (corresponding to days when temperature exceeded 25°C), computed by index SU25, have increased over the analysis period for all cities except for Multan (Figure 15). The increase was significant for Rawalpindi, Bahawalnagar, and Faisalabad (Table 3). A regionally averaged increase in the rate of SU25 was 0.315 calculated from −0.489, 0.635, 0.491, 0.412, and 0.524 for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi, respectively. Converting the above rates to a number of days per decade for above cities corresponds to −4.73, 6.14, 4.75, 3.98, and 5.07 days per decade, respectively, resulting in regional averages of 3.04 and 4.98 days per decade excluding Multan. Bahawalnagar had the highest increase in summer days (i.e., slightly over 6 days per decade), probably because of its vicinity in the Cholistan Desert, which covers an area of 26 300 km^2 and adjoins the Thar Desert, extending over to Sindh and into India.

There was no profound relationship of increase of the number of summer days with elevation that was consistent with the findings reviewed in literature that report that warming with elevation is not universally accepted and some observational studies show contrasting patterns (You et al. 2008). Vuille et al. (Vuille et al. 2003) reported that lower elevations to the west of the Andes in South America experienced

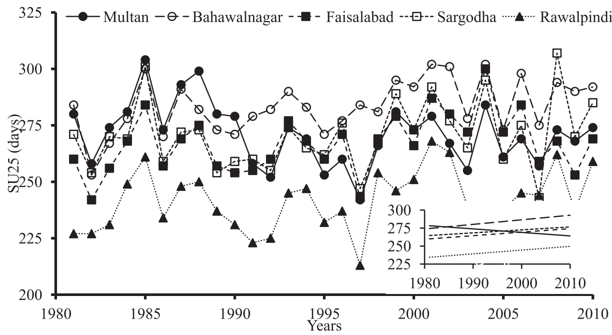

Figure 15. Averaged anomalies of annual SU25 (for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

the greatest warming while warming at higher elevations to the east is moderate. Pepin and Seidel (Pepin and Seidel 2005) found, through a global analysis of 1084 homogenous stations from the Global Historical Climate Network and Climate Research Unit datasets, that there was no systematic relationship between temperature trend magnitude and elevation. They even reported a decrease in trend magnitude with elevation in South America.

3.3.4. Tropical nights

Tropical nights (corresponding to nights when temperature exceeded 20°C), computed by index TR20, have increased for all cities (Figure 16). The increase was significant for all cities except Multan (Table 3). Regionally averaged increase in the rate of TR20 was 0.864 calculated from the individual rates 0.311, 0.862, 0.899, 0.943, and 1.31, for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi, respectively. Converting the above rates to a number of nights per

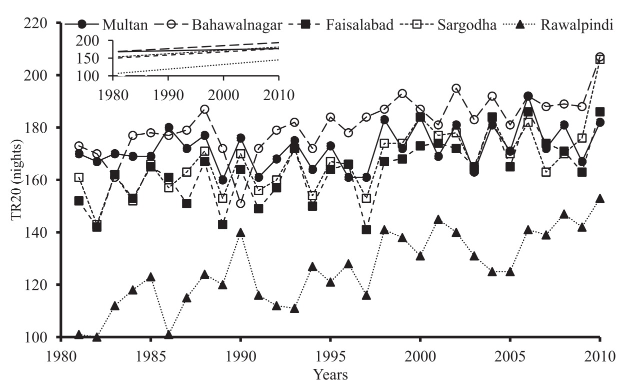

Figure 16. Averaged anomalies of annual TR20 (for the 1981–2010 analysis period) for selected cities. Insets show trend lines. Axes and lines of both figures have similar labels and types, respectively.

decade for above cities corresponds to 3.01, 8.33, 8.69, 9.12, and 12.6 nights per decade, respectively, with a regional average of 8.35 nights per decade. An increase in number of tropical nights was systematic with increase in mean sea level. A lesser increase in number of tropical nights for the cities at lower elevation reflects stability in the weather of these cities over the analysis period. Profound changes have occurred in elevated cities than those at lower elevation in consistence with reports in literature. Beniston and Rebetez (Beniston and Rebetez 1996) reported that warming at higher elevations was more pronounced than at lower elevations in Switzerland, consistent with the results derived from a nested regional climate model over the Alpine region (Giorgi et al. 1997). Fyfe and Flato (Fyfe and Flato 1999) also reported a significant increase of the simulated surface screen temperature over the Rocky Mountains in winter and spring, with more pronounced changes at higher elevations. For an analysis period of 1971–2004, Yang et al. (Yang et al. 2006) found linear rates of temperature increase in the Mt. Qomolangma region above averages for China and the globe. You et al. (You et al. 2008) reported a more rapid change in temperature at some high mountains in the Tibetan Plateau than that at low elevations.

An increase in tropical nights was double that in summer days. These results concur with the findings of Folland et al. (Folland et al. 2001), who reported that the nighttime temperature over land has increased by about twice the rate of the daytime temperature during the past 50 years. An increase in both tropical nights and summer days reflects an overall warming trend in the region.

4. Conclusions

Statistically significant trends in temperature indices depict overall warming in the regions. The frequency of extremely cold days and nights decreased and the frequency of extremely hot days and nights increased during the analysis period. Moreover, hot extremes generally had trends of greater magnitude than their cold counterparts, suggesting that the warm tails of the daily temperature distribution were changing faster than cold tails. This implies that the shape of the distribution of daily temperature extremes changed along with their historical mean values. Overall, analysis of temperature extremes showed a consistent pattern of warming across the selected cities of Punjab, Pakistan. Increased temperature in urban areas causes a change in the energy balance of the urban areas, often leading to higher temperatures than surrounding rural areas under the phenomenon of urban heat island effect. In changed climates, although the increased temperature in rural areas will offset the cooling phenomenon of vegetation to a certain extent, the warm weather in Multan and Sargodha will produce marketable mango and citrus. However, frequent droughts in Multan, as compared to other cities (Abbas et al. 2013), may further increase under warmer climate and adversely affect the mango and citrus production in the region. Persistently high temperatures affect internal quality of citrus and mango fruits. High total solids content are possible in fruits developing in a hotter climate. Fruit developing under warmer climates reach marketable sugar/acid ratios sooner than those developed under cooler climates.

Among other factors, the crop water requirement is a function of hot day attributes including temperature, radiation intensity, and humidity. An increase in the number of hot days means increased crop water requirements in the region.

Increased evapotranspiration means imbalance in the soil moisture system since the region receives uneven monsoons and an interrupted supply of canal water. Occurrence and persistence of heat waves will rise in future posing another challenge to meeting the increased crop water requirement for sustainable crop production, especially in the regions such as Faisalabad where saline groundwater not suitable for crops (Rasul et al. 2012). There is a need to study the effects of these elevated temperatures on heat units for field as well as for fruits crops, plant phenology, fruits quality, and evapotranspiration.

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