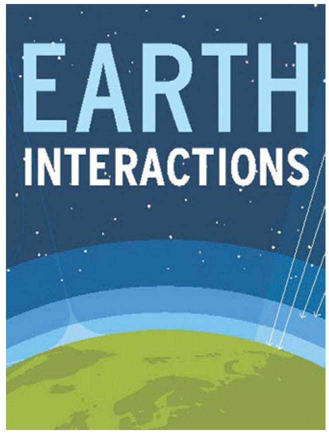

Patterns of Climate Extremes in the Coastal and Highland Regions of Balochistan, Pakistan

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ABSTRACT: Climatic extremes have direct and indirect effects on an ecosystem, whereby thermal variations bring warm and cold weather, and hydrological anomalies cause droughts and floods. Changing patterns of 13 temperature and 11 precipitation extreme indices for a 36-yr period (1980–2015) for four cities of the Balochistan province of Pakistan (Pasni, Jiwani,

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Khuzdar, and Dalbadin) were computed using RClimdex. A nonparametric Mann–Kendall test and Sen's slope estimates were used to determine the statistical significance and magnitude of a trend, respectively. Most of the indices calculated for temperature extremes show statistically significant changes in their historic pattern, depicting a clear picture of warming in the regions. The indices calculated for precipitation extremes show statistically significant as well as nonsignificant results, depicting asymmetrical droughts in the region. If the patterns of humid weather with hot and wet extremes in the coastal cities of Balochistan continue for a couple of future decades, there will be challenges in implementing the multibillion-dollar Balochistan coastal development projects of the Pakistani port of Gwadar—a doorway to the Middle East for Chinese-planned business endeavors through Pakistan.

KEYWORDS: Climate change; Climate classification/regimes; Climate variability

1. Introduction

Global warming has increased the severity and frequency of extreme weather events worldwide; many of the observed changes are unprecedented over decades to millennia. It is very likely that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale. The Intergovernmental Panel on Climate Change (IPCC; IPCC 2013) reported the global surface temperature is expected to rise about 1.5°C by the end of the year 2100 relative to 1850 to 1900 for all representative concentration pathway (RCP) scenarios. except RCP2.6. The RCPs are four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its Fifth Assessment Report (AR5). The AR5 supersedes the Special Report on Emissions Scenarios (SRES) projections published in 2000. The RCP2.6 emission and concentration pathway is representative of the literature on mitigation scenarios aiming to limit the increase of global mean temperature to 2°C (van Vuuren et al. 2011).

During the previous century, the Northern and Southern Hemispheres experienced an alarming rate of change in average surface temperature, equal to 2.37° and 1.30°C $(100\,\mathrm{yr})^{-1}$, respectively (Gil-Alana 2008). Donat et al. (2013) found a significant warming of both maximum (TX) and minimum (TN) temperatures over global land areas since 1950. The studies have reported a large spatial and temporal variability in the patterns of temperature and precipitation extremes worldwide, including in Pakistan (Abbas 2013; Abbas et al. 2014, 2018; Galarneau et al. 2012; Lau and Kim 2012; Yao and Chen 2015; van Wijngaarden 2015; Balling et al. 2016; Sen Roy et al. 2016). Other than temporal variations, there are substantial regional variations in the trends of temperatures driven by land-use/land-cover changes, including the role of the urban heat island (UHI), deforestation, agriculture-related irrigation effects, and other anthropogenic activities (Stocker et al. 2013; Sen Roy et al. 2016). Balling et al. (2016) reported several identifiable anthropogenic signals in the temperature records from Iran, but unlike most other studies (e.g., Wang et al. 2013; Lu and Liu 2014; Mohan and Kandya 2015), the reported signals were stronger with indices related to maximum rather than to minimum temperatures.

The assessment and predictability of extreme events is a challenging task because in order to understand regional climatic patterns, it is necessary to monitor how often the extreme events happen at a regional level/scale (Llano and Penalba

2011). Brunetti et al. (2004) investigated patterns for temperature and precipitation extremes in Italy during the last century and reported an overall increase in the intensity and frequency of precipitation extremes from 1951 to 2000 in the southern part of the country. An increase in the percentage of warm nights and a decrease in the percentage of cool nights have been reported for the western and eastern coasts of South America (Vincent et al. 2005). Increases in trends among the cold and warm trials of the daily minimum and maximum temperature frequencies have been reported during the latter half of the twentieth century for Europe (Klein Tank and Können 2003) and for central and South Asia (Klein Tank et al. 2006). About 61% of the time series studied by Roy and Balling (2004) showed an upward trend for precipitation in India. Similar findings (i.e., significant increases in rainfall trends) have been reported for various parts of India by Goswami et al. (2006) and Sen Roy (2009). Historically, Pakistan experienced variable rainfall patterns (Zahid and Rasul 2011).

Changes in the patterns of weather extremes (temperature and precipitation), especially for regions that are less reported in the literature, are important to evaluate in order to predict the variability in these climate change scenarios (Alexander et al. 2006; Webster et al. 2011). This study examined the variability and change in the extreme weather events during a 36-yr analysis period (1980–2015) in the province of Balochistan, Pakistan, which has been only a small focus in climate change literature but a larger focus with regards to Chinese business endeavors through the deep and hot waters of the Balochistan coast of Pakistan.

2. Materials and methods

2.1. Study site

Pakistan is an agricultural country with geographical coordinates 61.78°N latitude and 23.38°E longitude. Balochistan, which is the largest province of Pakistan with respect to area (347 190 km^2) and the smallest with respect to population (6.5 million), is famous for growing fruit orchards of all kinds specific to arid, mountainous, and tropical lands. This province has a peculiar geographic location, as it is bordered by Afghanistan to the northwest, Iran to the southwest, the Arabian Sea to the south, the Punjab and Sindh provinces of Pakistan to the east, and Khyber Pakhtunkhwa to the northeast (Figure 1). Its altitude ranges from sea level on the coastal plain to 1500–2000 m (the Iranian plateau) and over 3500 m in the north and northeast. Climatic conditions are continental (cold winters and hot summers) in the upper highland areas and subtropical (cool to mild winters and warm summers) in the lowland and plains areas (Chaudhry and Rasul 2004). The highest recorded temperature is 52°C, with averaged annual precipitation ranges from 400 mm in the highland areas to 100 mm in the lowland and plains areas.

This province is rich in exhaustible and renewable natural resources, and it is the second major supplier of natural gas in Pakistan. In April 2015, Pakistani and Chinese officials signed a series of more than 50 accords to inaugurate the China–Pakistan Economic Corridor, which will create a network of roads, railways, and pipelines linking China's restive west to the Arabian Sea through Pakistan. Keeping in mind the importance of Balochistan, its cities—including Pasni and Jiwani in the coastal areas, Dalbadin in the northwestern hilly area, and Khuzdar in

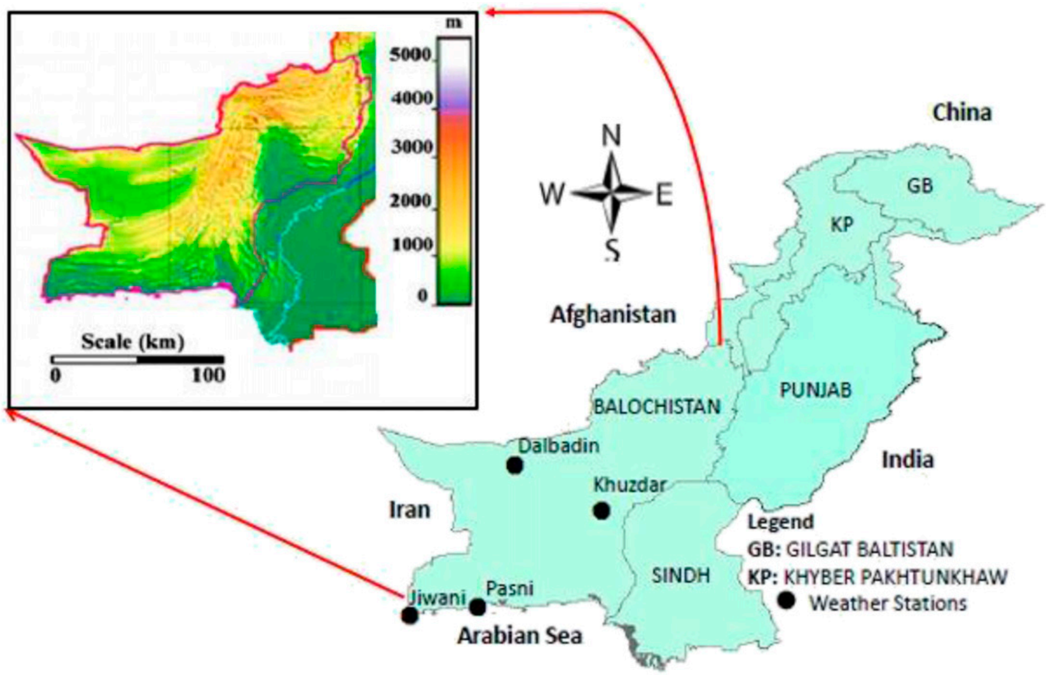

Figure 1. A reference map of the Balochistan province of Pakistan showing all the study locations, including Pasni, Jiwani, Dalbadin, and Khuzdar. The inset map shows the topography of Balochistan.

the central (mountainous) area of the province—were selected to represent the topography of Balochistan, with an emphasis on elevation representation for spatial variability observations and historical variations in mean daily precipitation (Table 1).

2.2. Data collection, homogenization, and quality control

Daily maximum and minimum temperature and precipitation data during the 36-yr period (1980–2015) from the selected cities (Table 1) were obtained from

Table 1. Population, geographical coordinates, and climatic parameters of the selected cities of Balochistan tabulated on basis of their elevation (Elev) above mean sea level (MSL). The weather stations are installed in the urban setup of these cities. Precipitation is denoted by *P*.

Stations	Population × 1000	Elev (MSL)	Lon (°)	Lat (°)	Daily *P* (mm)	Upper Tmax (°C)[a]	Lower Tmin, (°C)[b]
Pasni	367	6	63.47	25.26	0.1	30	19
Jiwani	237	57	61.75	25.05	1.3	33	21
Dalbadin	300	847	64.41	28.89	2.6	35	24
Khuzdar	417	1218	66.64	27.74	4.2	36	22

[a] Upper threshold of daily maximum temperature.
[b] Lower threshold of daily minimum temperature.

the Pakistan Meteorological Department and from an online source, OGIMET (www.ogimet.com/gclimat.phtml.en), which derives data from the National Oceanic and Atmospheric Administration's (NOAA) Global Summary of the Day. The weather stations are installed in the urban setup of the selected cities. The application of quality control procedures and the homogeneity tests were applied using RClimdex software (Zhang and Yang 2004). The software (version 1.4), developed at the Climate Research Branch of the Meteorological Service of Canada (Zhang and Yang 2004), was used for data quality assessment and calculation of temperature and precipitation indices (Alexander et al. 2006). The software also ensures that the precipitation data are error free, such that negative precipitation (if any) is marked to be replaced as missing data. Precipitation values above 200 mm were checked to ensure that the adjacent values were not set to missing, that is, that high values were not due to accumulation over several days (Aguilar et al. 2005).

2.3. Indices calculations

The 13 temperature and 11 precipitation indices (Table 2) jointly established by the Experts Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) and the World Meteorological Organization (WMO) Commission for Climatology and the Research Programme on Climate Variability and Predictability (CLIVAR) were used to study climate extremes of the four selected cities of Balochistan. Details on the nature and attributes of these indices are given in Abbas (2013) and Abbas et al. (2014).

2.4. Descriptive statistics

The nonparametric Mann–Kendall test (Mann 1945; Kendall 1955) and Sen's slope estimates (Sen 1968) were used to calculate trends in the selected time series of temperature and precipitation data. All the trend analyses were performed using MAKESENS (Salmi et al. 2002), which uses two different approaches to test for trend in a given time series based on the number of observations. If the number of observations is fewer than 10, MAKESENS uses the S statistics (Gilbert 1987); otherwise, it uses Z statistics (normal distribution). Detailed descriptions of the program can be found in Salmi et al. (2002).

3. Results and discussion

3.1. Indices of temperature extremes

Significance levels of change in the trends of temperature indices are shown in Table 3. There were significant or highly significant changes in the patterns of most of the indices, depicting spatial (from coast to mountains) and temporal (over a period of 3.6 decades) variability in temperature extremes in the province of Balochistan. Decadal increases in the number of warm days/nights and decreases in the number of cool days/nights concur with the findings of Choi et al. (2009). For Asia–Pacific network countries, Choi et al. (2009) reported that the annual

Table 2. Temperature and precipitation indices (abbreviations, definitions, and their units).

Indices	ID	Indicator name	Definitions	Units
Temperature indices	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 Tmin (coldest night)	Monthly minimum value of daily minimum temperature	°C
	TNx	Maximum Tmin (hottest night)	Monthly maximum value of daily minimum temperature	°C
	TXn	Minimum Tmax (coldest day)	Monthly minimum value of daily temperature	°C
	TXx	Maximum Tmax (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
Precipitation indices	CDD	Consecutive dry days	Maximum number of consecutive days with rainfall < 1 mm	Days
	CWD	Consecutive wet days	Maximum number of consecutive days with rainfall ≥ 1.00 mm	Days
	Rnn	Number of days above *nn* mm	Annual count of days when PRCPTOT ≥ *nn*, where *nn* is daily precipitation in mm	Days
	R10	Number of heavy precipitation days	Annual count of days when PRCPTOT ≥ 10 mm	Days
	R20	Number of very heavy precipitation days	Annual count of days when PRCPTOT ≥ 20 mm	Days
	R95p	Very wet days	PRCPTOT when precipitation > 95th percentile	mm
	R99p	Extremely wet days	PRCPTOT when precipitation > 99th percentile	mm
	SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCPTOT ≥ 1.0 mm) in the year	mm day^{-1}
	RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
	RX5day	Max 5-days precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
	PRCPTOT	Annual total wet-day precipitation	PRCPTOT in wet days (rainfall ≥ 1.00 mm)	mm

Table 3. Sen's slope estimate and significance levels between the calculated trends of temperature and precipitation extremes for the selected cities during the period of 1980–2015. Four significance levels are presented; see footnotes below.

Indices	Pasni	Jiwani	Dalbadin	Khuzdar
TN10p	−0.16[c]	−0.02	0.41[d]	−0.03
TN90p	0.18	0.04	−0.20[b]	0.37[d]
TX10p	−0.08	−0.09	0.19[a]	−0.17 [b]
TX90p	0.07[b]	0.25[b]	0.61[d]	0.15[a]
TXn	0.06	−0.10	−0.37[c]	−0.03
TXx	0.05	0.13[b]	0.19[c]	0.07[a]
TNn	0.04	−0.17[c]	−0.15[c]	0.04[b]
TNx	−0.06	0.05	0.06[a]	−0.07[a]
DTR	−0.02[a]	0.10[b]	0.25[d]	0.04
CSDI	−0.22[c]	−0.20[d]	−0.12[c]	−0.22[d]
WSDI	0.36[d]	0.23[d]	0.20[c]	0.21[d]
SU25	0.26	0.67[b]	0.40	1.07[b]
TR20	0.80[d]	0.61[c]	0.64[b]	0.34[d]
CDD	0.44	0.59	0.10	0.48
CWD	−0.17[d]	−0.13[d]	−0.10[d]	−0.10[c]
Rnn	−0.10	−0.04	−0.06	−0.04
R10	0.01	0.02	−0.10[b]	−0.06
R20	−0.003	−0.003	−0.07[c]	−0.008
R95p	−0.16	−0.25	−0.84	−0.48
R99p	−0.74	0.20	−0.38	−0.42
SDII	−0.09	−0.02	−0.34[d]	−0.18[b]
RX1day	−0.55	0.15	−0.59[b]	−0.17
RX5day	−0.47	−0.18	−0.76	−0.24
PRCPTOT	−0.95	−0.37	−0.91	−0.83

[a] Significance level ≤ 90%.
[b] Significance level ≤ 95%.
[c] Significance level ≤ 99%.
[d] Significance level ≤ 99.9%.

frequency of cool nights (days) decreased by 6.4 nights per decade (3.3 days per decade), and the frequency of warm nights (days) increased by 5.4 nights per decade (3.9 days per decade).

3.1.1. Cool nights (TN10p)

Averaged changes in the percentage of nights when daily minimum temperature falls below its 10th percentile (TN10p) were calculated annually during the analysis period (1980–2015) and are shown in Figure 2a. Overall, a decreasing trend is apparent for TN10p in the selected cities, except Dalbadin, and trends were found to be statistically significant for Pasni and Dalbadin. Linear trends (in percentage of nights) for Pasni, Jiwani, Dalbadin, and Khuzdar were −0.16, −0.02, 0.41, and −0.03, respectively. Converting percentages to nights, these correspond to trends of −1.28, −0.16, 3.30, and −0.24 nights per decade, with an average increase of 0.96 nights per decade in the region. The regionally averaged linear trend (in percentage of nights) was 0.05 for the analysis period. The selected region experienced the maximum percentile of cool nights during 1995, 2001, 2008, and 2014, respectively.

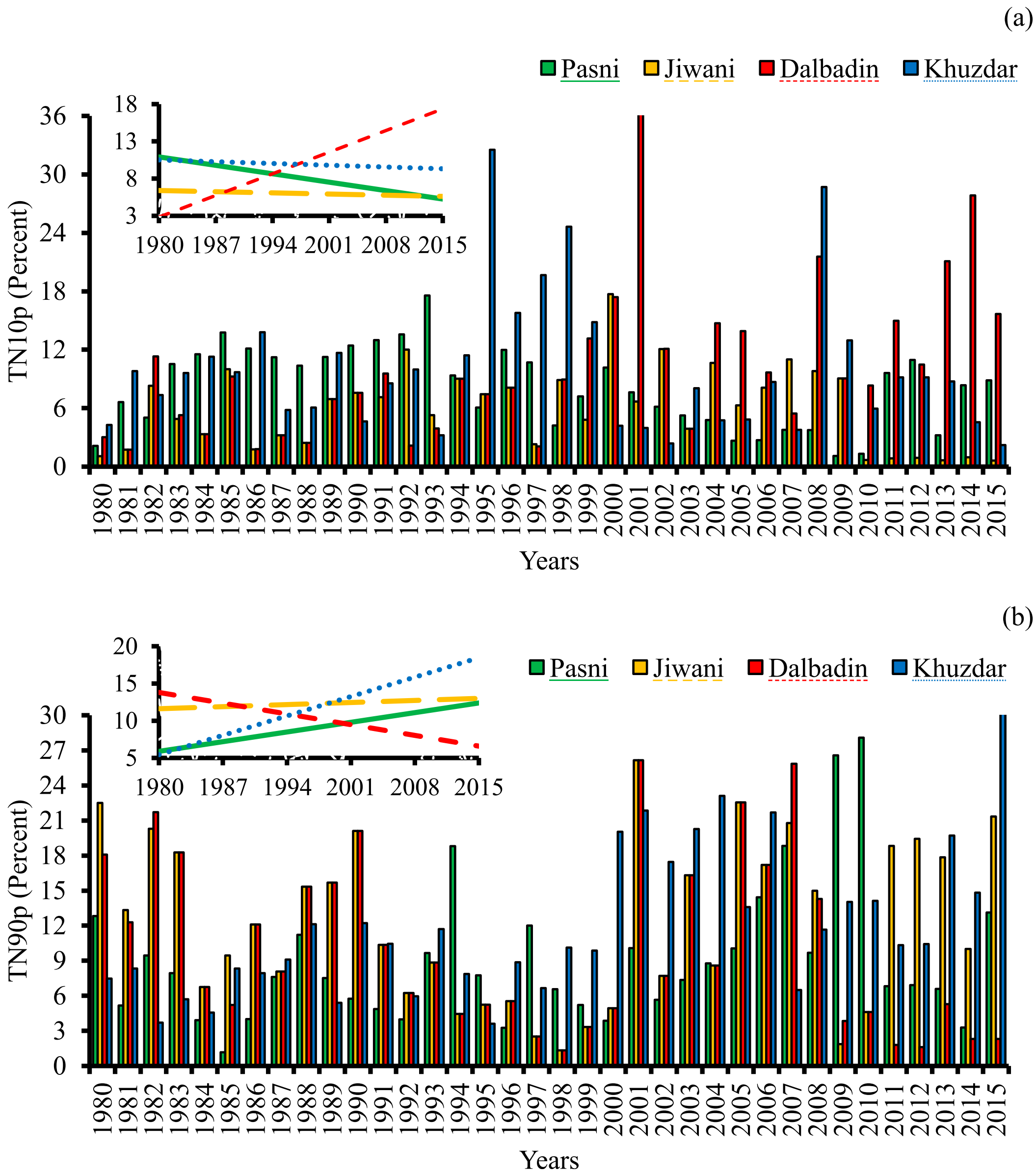

Figure 2. Annual averaged changes in the anomalies of (a) cool nights (represented by index TN10p) and (b) hot nights (represented by index TN90p) during the period of 1980–2015. Trend lines are shown in the insets, having the same axes labels as those of main graphs.

3.1.2. Hot nights (TN90p)

Figure 2b represents the magnitude and frequency of the calculated index of TN90p (percentage of nights when daily minimum temperature rises above its 90th percentile) during the analysis period of 1980–2015. An increasing trend has been observed in the index for all selected cities, except Dalbadin, and calculated trends are found to be statistically significant for Dalbadin and Khuzdar only. Linear trends (in percentage of nights) for Pasni, Jiwani, Dalbadin, and Khuzdar were 0.18, 0.04, −0.20, and 0.37, respectively. Converting percentages to nights, these correspond to trends of 1.45, 0.32, −1.61, and 2.98 nights per decade, with an average increase rate of 0.56 nights per decade in the region. The regionally averaged linear trend (in percentage of nights) was 0.09 for the analysis period. The selected region experienced the maximum percentile of hot nights during 2001; 2007 and 2009; 2010, and 2015, respectively.

3.1.3. Cool days (TX10p)

Averaged changes in the percentage of days when daily maximum temperature falls below its 10th percentile (TX10p) were investigated annually during the analysis period (1980–2015) and are shown in Figure 3a. A decreasing trend has been apparent in the TX10p index for all cities, except Dalbadin, while the localities of Dalbadin and Khuzdar exhibited statistically significant results. Linear trends (in percentage of days) for Pasni, Jiwani, Dalbadin, and Khuzdar were −0.08, −0.09, 0.19, and −0.17, respectively. Converting percentages to days, these correspond to trends of −0.64, −0.72, 1.53, and −1.37 days per decade, with an averaged decrease rate of −0.18 days per decade in the region. The regionally averaged linear trend (in percentage of days) was −0.037 for the analysis period. All cities in the province experienced the most frequent cool days during 1983 and 1992. Overall, a decreasing trend is apparent for TX10p in the region.

3.1.4. Hot days (TX90p)

Figure 3b represents the magnitude and frequency of the calculated index TX90p (percentage of days when daily maximum temperature rises above its 90th percentile) during the analysis period of 1980–2015. A statistically significant and linearly increasing trend for TX90p has been observed in all the selected cities. Linear trends (in percentage of days) for Pasni, Jiwani, Dalbadin, and Khuzdar were 0.07, 0.25, 0.61, and 0.15, respectively. Converting percentages to days, these correspond to trends of 0.56, 2.01, 4.91, and 1.20 days per decade, with an average increase rate of 2.71 days per decade in the region. The regionally averaged linear trend (in percentage of days) was 0.27 for the analysis period. All cities in the province experienced the most frequent hot days during 2008, 2009, 2010, and 2015. Overall, an increasing trend is apparent for TX90p, indicating that hot days have significantly increased across the selected region from 1980–2015.

3.1.5. Coldest days (TXn)

The monthly minimum values of daily maximum temperature (i.e., TXn) representing the coldest day's temperature variations on an annual scale for the selected cities are shown in Figure 4a. A decreasing trend is apparent for all selected cities, except Pasni, in the abovementioned index. Linear slopes for Pasni, Jiwani, Dalbadin, and Khuzdar were 0.06, −0.10, −0.37, and −0.03, respectively. These slopes correspond to trends of 0.48°, −0.80°, −2.98°, and −0.24°C decade^{-1}. The regionally averaged slope of the coldest day's index is −0.11, which corresponds to an increasing trend in the coldest day frequency equivalent to −1.34°C

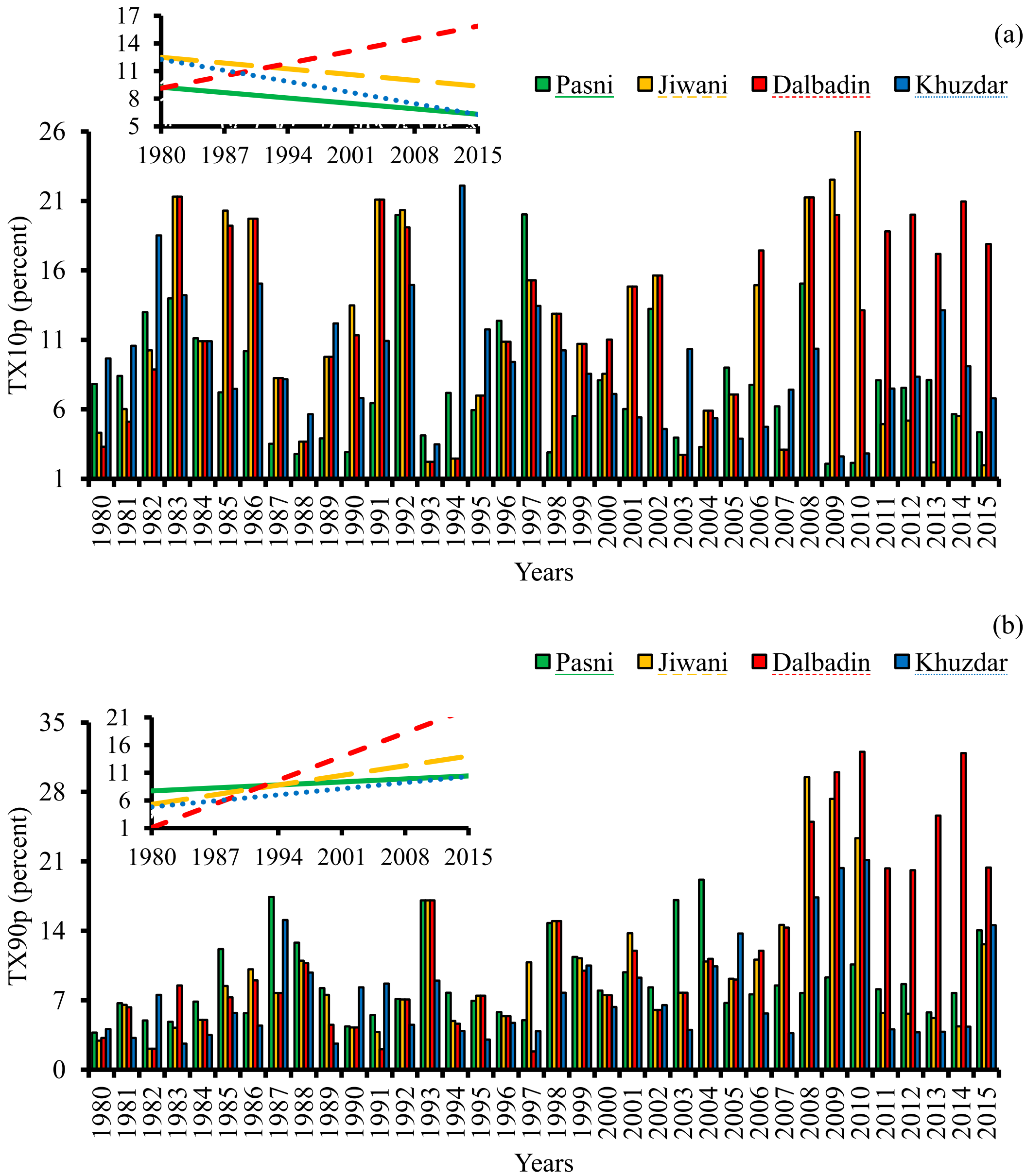

Figure 3. As in Figure 2, but for (a) cool days (TX10p) and (b) hot days (TX90p).

decade^{-1}. The lowest averaged annual temperatures of the coldest days for Pasni, Jiwani, Dalbadin, and Khuzdar were 3.5°C in 1991, 3.5°C in 2008, 4.5°C in 2008, and 4.6°C in 1984, respectively.

3.1.6. Hottest days (TXx)

The averaged variability and changes in the monthly maximum of daily maximum temperatures (i.e., TXx) during the analysis period of 1980–2015 are shown

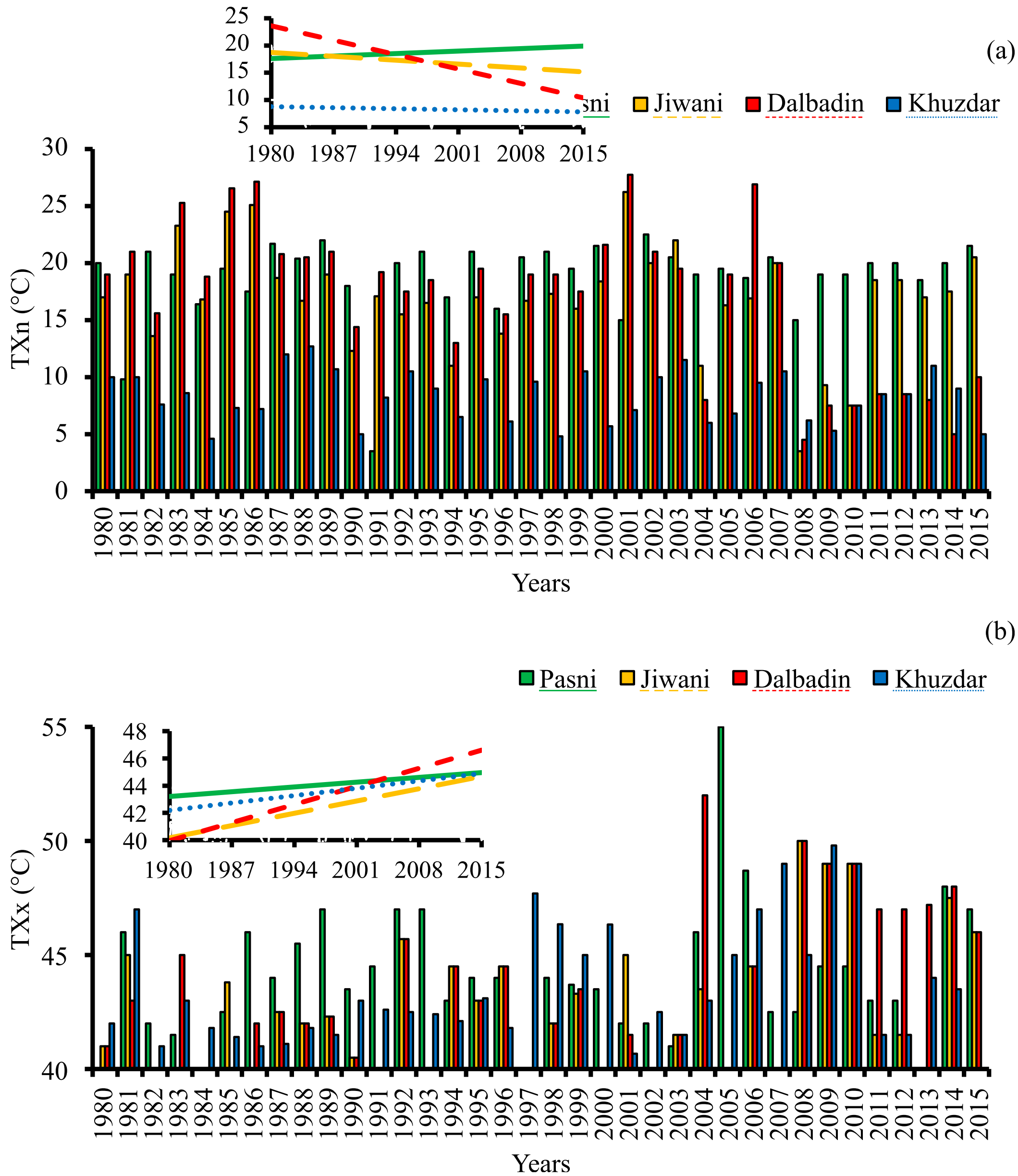

Figure 4. As in Figure 2, but for (a) coldest days (TXn) and (b) hottest days (TXx).

in Figure 4b. Overall, an increasing trend has been observed for the TXx index among all the selected cities, and the trends were found statistically significant for Jiwani, Dalbadin, and Khuzdar. Linear slopes of the TXx index for Pasni, Jiwani, Dalbadin, and Khuzdar were 0.05, 0.13, 0.19, and 0.07, respectively. These slopes correspond to trends of 0.40°, 1.03°, 1.53°, and 0.56°C decade^{-1}. The regionally averaged slope for the TNx index is 0.11, which corresponds to the trend of 1.04°C decade^{-1}. The highest averaged annual temperatures of the TXx index for Pasni,

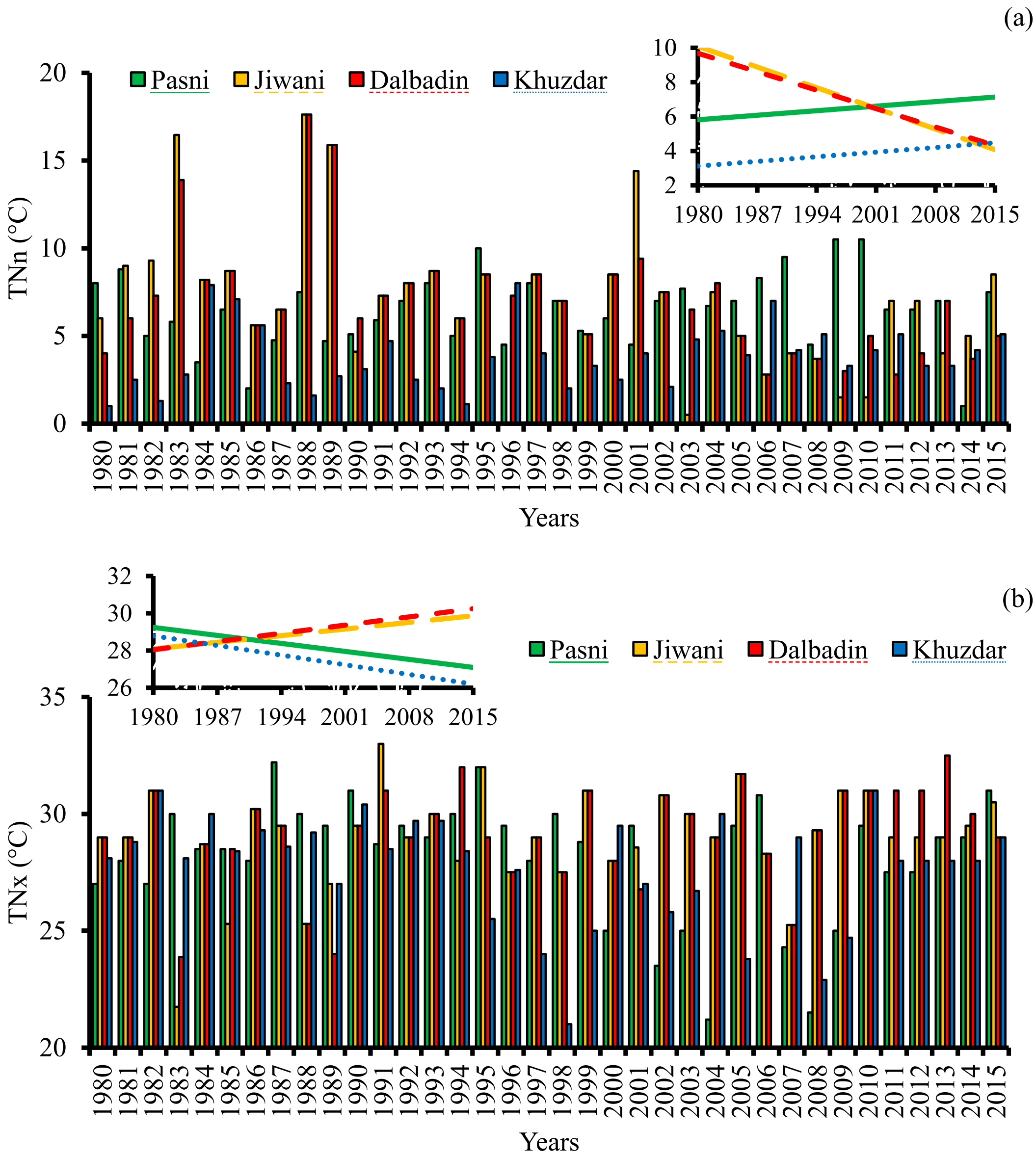

Figure 5. As in Figure 2, but for (a) coldest nights (TNn) and (b) hottest nights (TNx).

Jiwani, Dalbadin, and Khuzdar were 55°C in 2005, 50°C in 2008, 52°C in 2004, and 49.8°C in 2009, respectively.

3.1.7. Coldest nights (TNn)

Figure 5a shows the calculated trends in the monthly minimum of the daily minimum temperatures (i.e., TNn) during the analysis period of 1980–2015. A statistically significant and linearly decreasing trend has been observed in the TNn index for Jiwani and Dalbadin, compared to Pasni and Khuzdar, which shows an increasing trend for the TNn index and was found to be statistically significant for Khuzdar as well. Linear slopes of the TNn index for Pasni, Jiwani, Dalbadin, and Khuzdar were 0.04, −0.17, −0.15, and 0.04, respectively. These slopes correspond to trends of 0.32°, −1.37°, −1.20°, and 0.32°C decade^{-1}. The regionally averaged slope for TNn is −0.06, which corresponds to a trend of −0.75°C decade^{-1}. The lowest averaged annual temperatures of the TNn index for Pasni, Jiwani, Dalbadin, and Khuzdar were 1°C in 2014, 0°C in 1996, 2.8°C in 2006, and 1°C in 1980, respectively.

3.1.8. Hottest nights (TNx)

The averaged variability and changes in the monthly maximum of daily minimum temperature (i.e., TNx) during the analysis period of 1980–2015 are shown in Figure 5b. An increasing trend has been observed in the TNx index for Jiwani and Dalbadin, whereas Pasni and Khuzdar exhibited a decrease in the index. Statistically significant trends have been reported for the regions of Dalbadin and Khuzdar. Linear slopes of the TNx index for Pasni, Jiwani, Dalbadin, and Khuzdar were −0.06, 0.05, 0.06, and −0.07, respectively. These slopes correspond to trends of −0.48°, 0.40°, 0.48°, and −0.56°C decade^{-1}. The regionally averaged slope for the TNx index is −0.005, which corresponds to a trend of 0.10°C decade^{-1}. The highest averaged annual temperatures of the TNx index for Pasni, Jiwani, Dalbadin, and Khuzdar were 32.2°C in 1987, 33°C in 1991, 32°C in 1994, and 30.4°C in 1990, respectively.

3.1.9. Diurnal temperature range (DTR)

A linearly increasing trend has been observed for the diurnal temperature range (DTR) index (mean difference between maximum and minimum temperatures) in all the selected cities, except Pasni, and calculated trends were statistically significant for the localities of Jiwani and Dalbadin only. Linear slopes of the DTR index for Pasni, Jiwani, Dalbadin, and Khuzdar were −0.02, 0.10, 0.25, and 0.04, respectively. These slopes correspond to trends of −0.16°, 0.80°, 2.01°, and 0.32°C decade^{-1}. The regionally averaged slope for the DTR index is 0.09, which corresponds to a trend of 1.04°C decade^{-1}.

3.1.10. Cold spell duration indicator (CSDI)

The annual count of days with at least 6 consecutive days when the tail of minimum temperature fell below its 10th percentile [cold spell duration indicator (CSDI)] and the analysis period (1980–2015) is shown in Figure 6a. Statistically significant and linearly decreasing trends were apparent for the CSDI index in all the selected cities. Linear slopes of the CSDI index for Pasni, Jiwani, Dalbadin, and Khuzdar were −0.22, −0.20, −0.12, and −0.22, respectively. Converting the decreasing rate of the CSDI index to the number of occurrences of CSDI per decade, this corresponds to −1.77, −1.61, −0.96, and −1.77 days per decade in the selected regions, respectively. The regionally averaged occurrences were calculated to be −1.45 days per decade. The maximum CSDI values for Pasni, Jiwani, Dalbadin, and Khuzdar were recorded during 1993 (19 days), 1990 (22 days), 1986 (15 days), and 1984 (14 days), respectively.

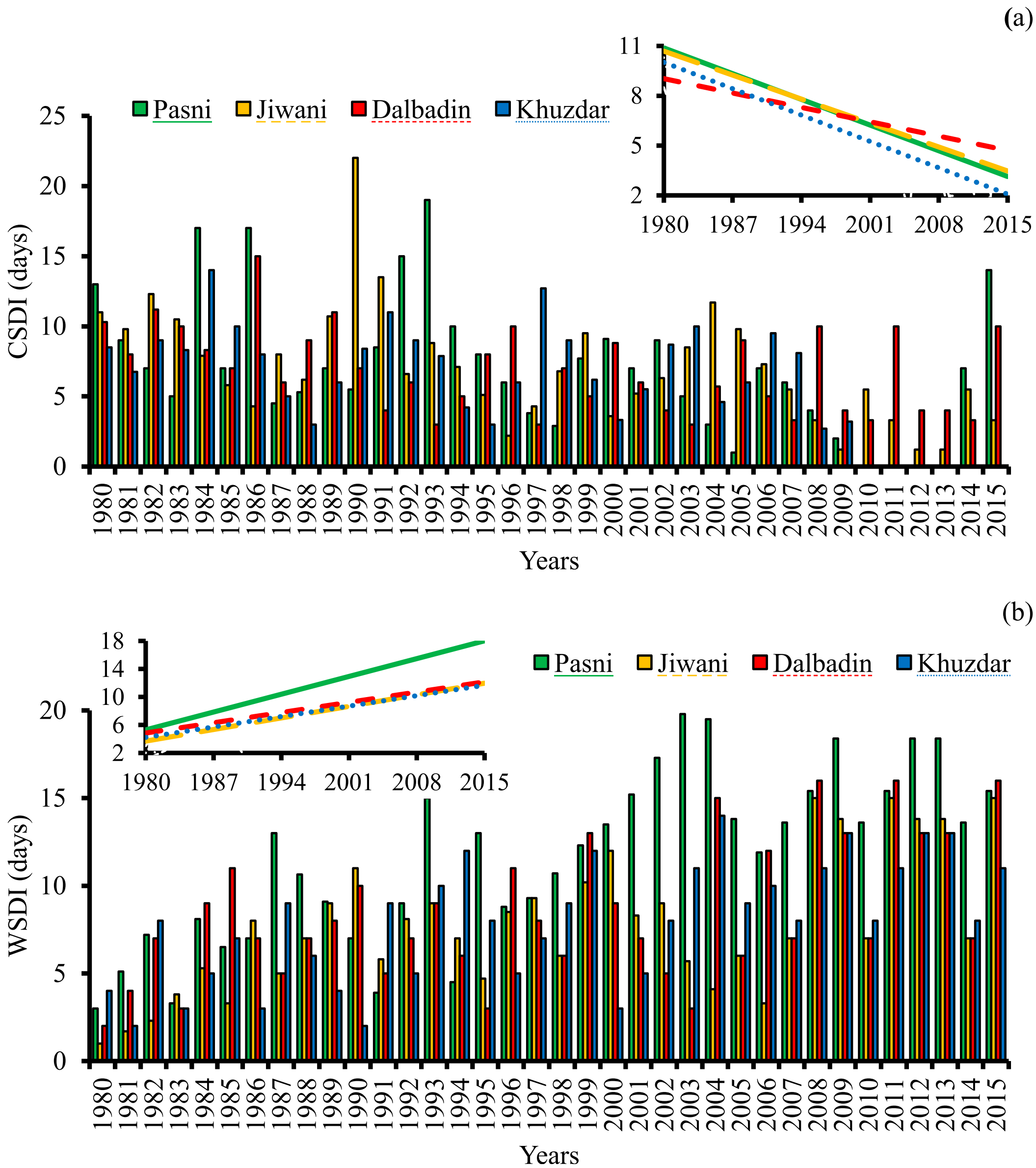

Figure 6. As in Figure 2, but for (a) CSDI and (b) WSDI.

3.1.11. Warm spell duration indicator (WSDI)

The annual count of days with at least 6 consecutive days when the tail of maximum temperature rises above its 90th percentile [warm spell duration indicator (WSDI)] and the analysis period (1980–2015) is shown in Figure 6b. A linearly increasing and statistically significant trend has been observed for the WSDI index in the selected cities. Linear slopes of the WSDI index for Pasni, Jiwani, Dalbadin, and Khuzdar were 0.36, 0.23, 0.20, and 0.21, respectively. Converting the increasing rate of the WSDI index to the number of occurrences of

WSDI per decade, this corresponds to 2.90, 1.85, 1.61, and 1.69 days per decade in the selected regions, respectively. Regionally averaged occurrences were calculated to be 1.71 days per decade. The maximum WSDI values for Pasni, Jiwani, Dalbadin, and Khuzdar were recorded during 2003 (19.8 days), 2008 (15 days), 2008 (16 days), and 2004 (14 days), respectively.

3.1.12. Summer days (SU25)

The annual count of days when the tail of maximum temperature exceeded 25°C (SU25) during the analysis period is shown in Figure 7a. Overall, an increasing trend is apparent for the SU25 index among the selected cities, and the calculated trends were statistically significant for Jiwani and Khuzdar. A regionally averaged increase in the rate of SU25 was 0.60, calculated from 0.26, 0.67, 0.40, and 1.07 for Pasni, Jiwani, Dalbadin, and Khuzdar, respectively. Converting the above rates to a number of days per decade for the above cities, this corresponds to 2.09, 5.39, 3.22, and 8.62 days per decade, respectively, resulting in a regional average of 5.74 days per decade. The maximum SU25 values for Pasni, Jiwani, Dalbadin, and Khuzdar were observed during 1993 (311 days); 2002 and 2004 (320 days); 2012 (336 days); and 2008, 2011, and 2015 (322 days), respectively.

3.1.13. Tropical nights (TR20)

The annual count of nights when the tail of minimum temperature exceeded 20°C (TR20) and the analysis period are shown in Figure 7b. A linearly increasing and statistically significant trend has been observed for the TR20 index among the selected cities. A regionally averaged increase in the rate of TR20 was 0.59, calculated from 0.80, 0.61, 0.64, and 0.34 for Pasni, Jiwani, Dalbadin, and Khuzdar, respectively. Converting the above rates to a number of nights per decade for the above cities corresponds to 6.44, 4.91, 5.15, and 2.73 nights per decade, respectively, resulting in a regional average of 4.27. The maximum TR20 values for Pasni, Jiwani, Dalbadin, and Khuzdar were observed during 2007, 2010, and 2014 (225 nights); 2005 (222 nights); 2003 (214 nights); and 2005 (216 nights), respectively.

3.2. Indices of precipitation extremes

Significance levels of change in the trends of precipitation indices are shown in Table 3. There were significant or highly significant changes in the patterns of most of the indices calculated for the elevated cities of Dalbadin and Khuzdar and in the patterns of the consecutive wet days (CWD) index for the two coastal cities of Pasni and Jiwani, depicting spatial (from coast to mountains) and temporal (over a period of 3.6 decades) variability in precipitation extremes in the province of Balochistan.

3.2.1. Consecutive wet days (CWD)

A linearly increasing trend is apparent for the CWD index, and the calculated trends were found statistically significant, depicting scarcity of water in the region.

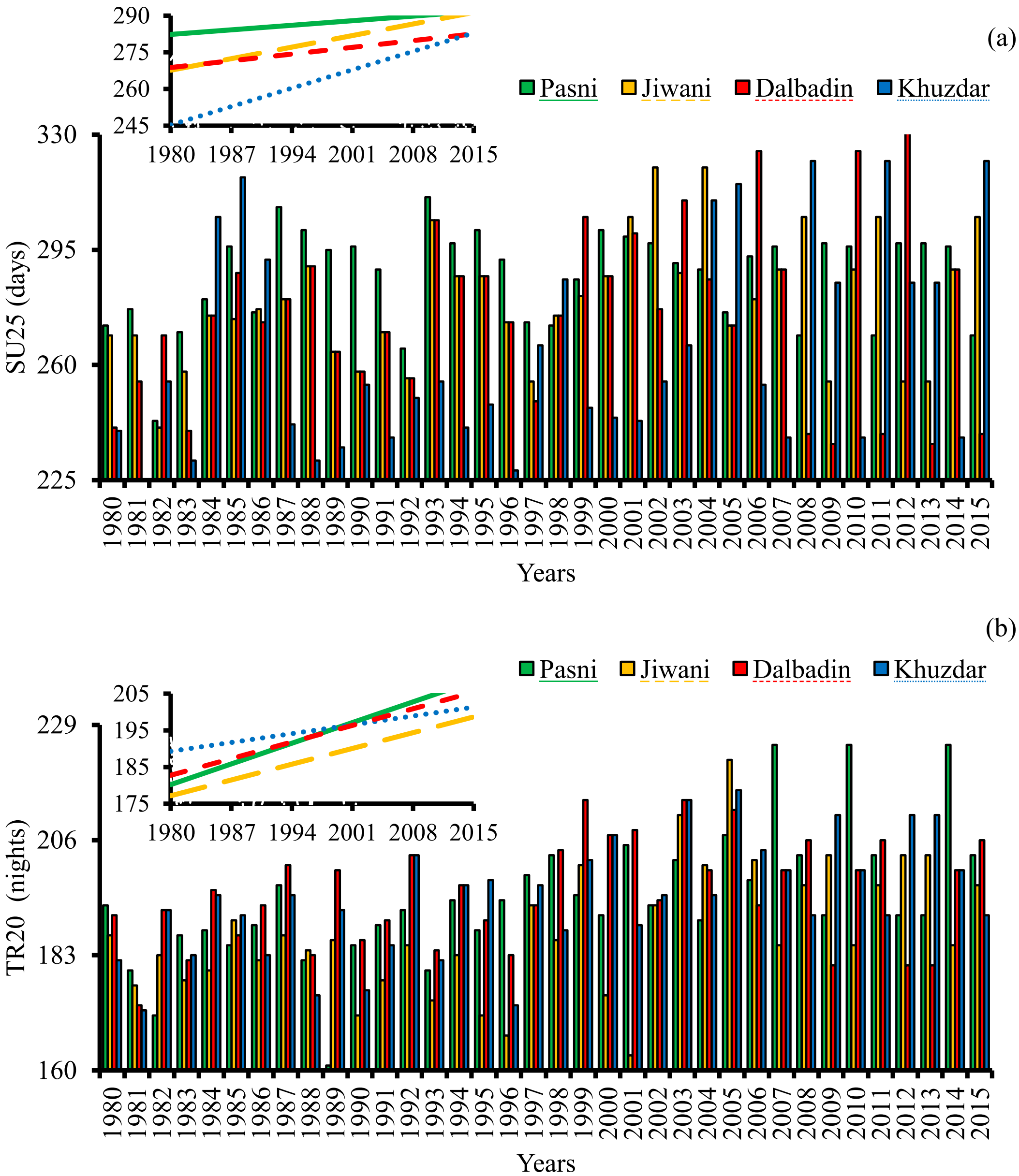

Figure 7. As in Figure 2, but for (a) summer days (SU25) and (b) tropical nights (TR20).

A regionally averaged decrease in the rate of CWD was −0.12, calculated from −0.17, −0.13, −0.10, and −0.10 for Pasni, Jiwani, Dalbadin, and Khuzdar, respectively. Converting the above rates to a number of days per decade for the above cities, this corresponds to −1.37, −1.04, −0.80, and −0.80 days per decade, respectively, resulting in an average decrease rate of 1.00 decade^{-1} for the region. Overall, the region experienced the maximum CWD during the period of 1981–87 and the minimum CWD during the period of 2000–06.

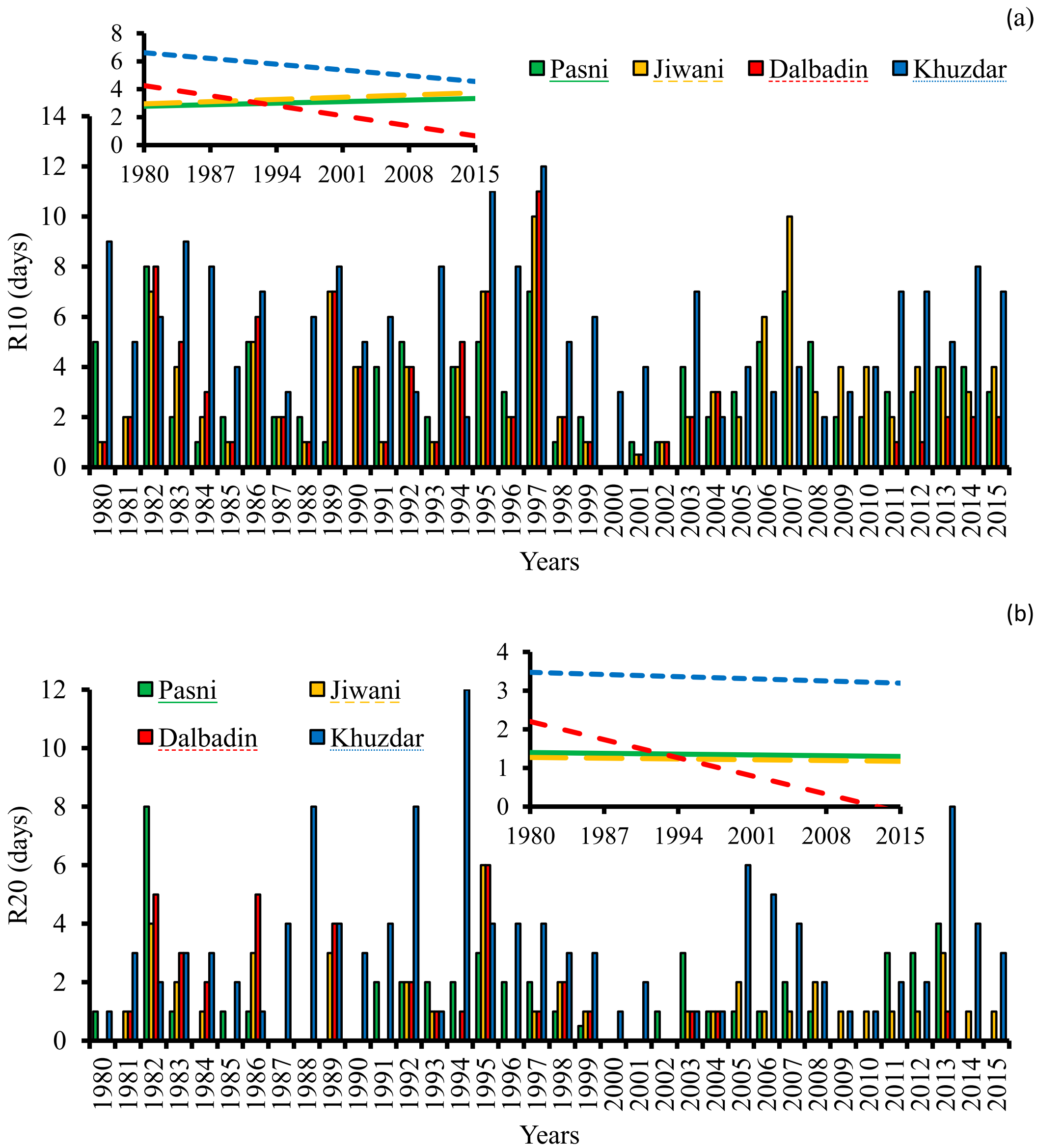

Figure 8. As in Figure 2, but for (a) heavy precipitation days (R10) and (b) very heavy precipitation days (R20).

3.2.2. Heavy precipitation days (R10)

Figure 8a shows the annual count of days above a precipitation threshold of 10 mm (R10) during the analysis period of 1980–2015. A linearly decreasing trend is apparent for the R10 index, except in Pasni and Jiwani. The calculated trends were found to be statistically significant for Dalbadin. Linear slopes of the R10 index for Pasni, Jiwani, Dalbadin, and Khuzdar were 0.01, 0.02, −0.10, and −0.06, respectively. These slopes correspond to trends of 0.12, 0.17, −0.80, and −0.48 $decade^{-1}$. The regionally averaged slope for the R10 index is −0.03, which corresponds to a trend of $-0.24\,\mathrm{decade}^{-1}$. The maximum R10 values for Pasni, Jiwani, Dalbadin, and Khuzdar were observed during 1982 (8 days); 1997 and 2007 (10 days); 1997 (11 days); and 1997 (12 days), respectively. All the cities in the region experienced the highest R10 values during the period of 1995–97.

3.2.3. Very heavy precipitation days (R20)

The annual count of days above a precipitation threshold of 20 mm (R20) and the analysis period (1980–2015) are shown in Figure 8b. Overall, there is a a decreasing trend for the R20 index in the selected cities. The calculated trends were found statistically nonsignificant for all the cities, except Dalbadin. Linear slopes of the R20 index for Pasni, Jiwani, Dalbadin, and Khuzdar were −0.003, −0.003, −0.07, and −0.008, respectively. These slopes correspond to trends of −0.02, −0.02, −0.56, and $-0.06\,\mathrm{decade}^{-1}$. The regionally averaged slope for the R20 index is −0.02, which corresponds to a trend of $-0.17\,\mathrm{decade}^{-1}$. The maximum R20 values for Pasni, Jiwani, Dalbadin, and Khuzdar were observed during 1982 (8 days), 1995 (6 days), 1995 (6 days), and 1994 (12 days), respectively.

3.2.4. Simple daily intensity index (SDII)

An overall decreasing trend has been observed for the simple daily intensity index (SDII) in all the selected cities. The calculated trends were found statistically significant for Dalbadin and Khuzdar. Linear slopes of the SDII for Pasni, Jiwani, Dalbadin, and Khuzdar were −0.09, −0.02, −0.34, and −0.18, respectively. These slopes correspond to trends of −0.77, −0.20, −2.73, and $-1.45\,\mathrm{decade}^{-1}$. The regionally averaged slope for the SDII is −0.16, which corresponds to a trend of $-1.29\,\mathrm{decade}^{-1}$. Pasni experienced the most and Jiwani experienced the fewest numbers of SDII. The maximum SDII values for Pasni, Jiwani, Dalbadin, and Khuzdar were observed during 1991 ($32.7\,\mathrm{mm\,day}^{-1}$), 1998 ($18\,\mathrm{mm\,day}^{-1}$), 1980 ($26.8\,\mathrm{mm\,day}^{-1}$), and 1980 ($22.9\,\mathrm{mm\,day}^{-1}$), respectively. The minimum SDII values for Pasni, Jiwani, Dalbadin and Khuzdar were 1981 ($1\,\mathrm{mm\,day}^{-1}$); 1985 ($5.2\,\mathrm{mm\,day}^{-1}$); 2009 and 2010 ($3.3\,\mathrm{mm\,day}^{-1}$); and 1990 and 2002 ($5.8\,\mathrm{mm\,day}^{-1}$), respectively.

3.2.5. Maximum 1-day precipitation (RX1day)

An overall decreasing trend has been observed for the RX1day index in all the selected cities, except Jiwani. The calculated trends were found to be statistically significant for Dalbadin only. Linear slopes of the RX1day index for Pasni, Jiwani, Dalbadin, and Khuzdar were −0.55, 0.15, −0.59, and −0.17, respectively. These slopes correspond to trends of −4.43, 1.20, −4.75, and $-1.37\,\mathrm{decade}^{-1}$. The regionally averaged slope for the RX1day index is −0.29, which corresponds to a trend of $-2.33\,\mathrm{decade}^{-1}$. Pasni experienced the most and Dalbadin experienced the fewest numbers of RX1day. The maximum RX1day values for Pasni, Jiwani, Dalbadin, and Khuzdar were observed during 1983 (141 mm); 2013 (45 mm); 1982, 1984, and 1994 (50 mm); and 1986 (53 mm), respectively. The minimum RX1day values for Pasni, Jiwani, Dalbadin, and Khuzdar were 1990 (8 mm), 2000 (6 mm), 2010 (11.3 mm), and 2008 (15 mm), respectively.

Table 4. Correlation coefficients between historical changes in population of the selected cities and temperature indices calculated from historical record of temperature extremes.

Indices	TN10p	TN90p	TX10p	TX90p	TXn	TXx	TNn	TNx	DTR	CSDI	WSDI	SU25	TR20
Population	0.50[a]	0.10[b]	0.12[b]	0.44[b]	0.51[a]	0.52[a]	0.18[b]	0.18[b]	0.52[a]	0.31[b]	0.78[a]	0.53[a]	0.52[a]

[a] Significant effect at $p \leq 0.05$.
[b] No significant effect.

4. Discussion and conclusions

Variations in regional weather extremes are dictated by an increased scale of anthropogenic activities that are directly related to the population increase in a region. Typical anthropogenic activities increase the effect of UHIs, decrease land cover through deforestation, and variate land-use change through agriculture and related irrigation effects. These activities affect weather processes, resulting in an increase in temperature and precipitation at random, as mentioned in the literature (Wang et al. 2013; Lu and Liu 2014; Mohan and Kandya 2015; Balling et al. 2016; Sen Roy et al. 2016).

Findings presented in Table 3 show a general warming trend in Balochistan. The frequency of extremely cold days and nights decreased and the frequency of extremely hot days and nights increased during the analysis period of 1981–2015. 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 the cold tails. This implies that the shape of the distribution of daily temperature extremes changed along with their historical mean values, as they did in the southwestern province of Sindh, Pakistan (Abbas et al. 2018). Overall, a consistent pattern of warming was observed across the selected cities of Balochistan, Pakistan. These findings are in concurrence with the literature that indicates an overall decrease in cold extremes and an increase in warm extremes since the middle of the twentieth century (Seneviratne et al. 2012). Increased temperature in urban areas causes a change in the energy balance of these areas, often leading to higher temperatures than those of the surrounding rural areas under the phenomenon of UHIs.

For the UHI phenomenon, historical population change data and the calculated temperature indices for the selected cities were correlated to determine the effect of population increase on the increase in temperature extremes. The increase in population was found to be linearly and statistically correlated with most of the temperature indices, including TN10p, TX10p, TXn, TXx, DTR, WSDI, SU25, and TR20 (Table 4). This showed the effect of UHIs on trends of cool nights, cool days, hottest nights, coldest days, diurnal temperature range, warm days, summer days, and tropical nights during the studied year. These results are in concurrence with the findings of Sen Roy et al. (2016) and Balling et al. (2016), regarding their similar reports on the effect of UHIs on most of the temperature indices mentioned here for various Iranian cities situated in the southwest of Balochistan.

Pasni experienced the hottest weather among the selected cities during the study period, followed by Jiwani. Provided these trends continue in the future, the increased warming would negatively affect the livelihood of the people of these two coastal cities who earn their bread and butter from small-scale fishing. Larger-scale statistics reflect the total fish production of Pakistan exceeds 55 000 metric tons, enlisting Pasni and Jiwani as the major fish hubs of Pakistan after Karachi and Gwadar. The Indian Ocean remains a source of fishing in southern, coastal regions of Pakistan (Bonfil 1994).

This resulted in the annual mean precipitation quantity for these two cities to be many times larger than the two coastal cities, Pasni and Jiwani, during very wet days than during extreme wet days. Being the coastal city, however, Pasni experienced continuous wet periods, as depicted by the changes in the SDII, referred to as annual total precipitation amount divided by the number of wet days during the analysis. Temperature and rainfall trends of the coastal areas may lead to further studies to associate these trends with an increasing trend of sea surface temperatures, since the findings of Rajeevan et al. (2008) supported the hypothesis that the increasing trend of extreme rainfall events in the past decades could be associated with the increasing trend of sea surface temperatures and surface latent heat flux over the tropical Indian Ocean.

Elevation had a significant impact on the precipitation received by the cities of Balochistan. Because of its high elevation, Khuzdar had higher values of R10 and R20, followed by Dalbadin, the midland-located city. Because of the lack of water storage facilities in Balochistan, water generated from rain on the highlands runs to the lowlands as a flash flood. This water is hardly useful for agricultural purposes in the midland areas in the neighborhood of Dalbadin, which experienced a warmer climate than Khuzdar. Increase in atmospheric temperature affects crop water requirement because of the increased solar radiation and humidity. Increased crop water requirements will put a burden on the already-water-scarce region of Balochistan, which is on its way to agricultural productivity through construction of a Head Regulator at Taunsa Barrage on the Indus River to put water into the Kachi Canal. This canal is about 500 km (300 km lined portion in Punjab and 200 km unlined portion in Balochistan), with a target distribution system of 1500-km length within Balochistan to provide a sustainable irrigation system to the province.

The majority of the indices showed warming trends, but there also were notable incidences that reflected cooling trends in Balochistan. For example, the selected region experienced the maximum percentile of cool nights during 1995, 2001, 2008, and 2014. There was a 0.05% regionally averaged cooling trend (extracted from cool night index data) in the region for the analysis period. There was an increase of 0.96 cool nights per decade in the region. Although there was an overall regionally averaged negative linear trend (in percentage of days, −0.037%) for the analysis period, the selected cities in the province experienced the most frequent cool days during the years 1983 and 1992. The lowest averaged annual temperatures of the coldest days for Pasni, Jiwani, Dalbadin, and Khuzdar were 3.5°C in 1991, 3.5°C in 2008, 4.5°C in 2008, and 4.6°C in 1984, respectively. The lowest averaged annual temperatures of the coldest nights for Pasni, Jiwani, Dalbadin, and Khuzdar were 1°C in 2014, 0°C in 1996, 2.8°C in 2006, and 1°C in 1980, respectively.

The warm and wet coasts of Balochistan produce challenging environments for developmental work of the planned China–Pakistan Economic Corridor and potential trade endeavors of China to the Middle East and Africa through the deep

Pakistani port of Gwadar. With a fully functioning Gwadar port, the population of the coastal areas of Balochistan and inland activities of various businesses will increase, posing a threat to the environment because of their anthropogenic activities, ranging from fishing and industrial operations to heavy traffic on road and rail networks through land-use/land-cover change.

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