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Surface Air Temperature Variability over Subregions of Pakistan During 1970–2014

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Abstract— This study examines seasonal and annual mean temperature changes from 1970 to 2014. Climatologically, the June–July–August season exhibited the highest (27 °C) mean temperatures over the country, followed by March–April–May (MAM; 20.2 °C), September–October–November (SON; 19.1 °C), and December–January–February (DJF; 8.8 °C), while the annual mean was 18.8 °C. The southern region exhibited higher mean temperatures than the northern region for the DJF, MAM, JJA, SON, and annual timescales during the study period. The seasonal trend across the country was highest in MAM (0.027 °C/year), followed by SON (0.025 °C/year), DJF (0.023 °C/year), and JJA (0.016 °C/year). The interannual trend increased significantly at 0.023 °C/year across the country. Across the north, MAM showed the highest increase (nonsignificant) in trends at 0.025 °C/year, followed by a significant increase during SON (0.018 °C/year), DJF (0.017 °C/year), and JJA (0.010 °C/year), while annual trends were the lowest (0.017 °C/year). Examination of abrupt change over Pakistan showed nonsignificant change during JJA, while MAM, JJA, SON, and annual timescales demonstrated significant positive and negative changes. Decadal anomalies showed long-term positive tendencies in DJF (since 1990–2014) temperature, followed by JJA, SON, annual, and MAM timescales (2000–2014). In conclusion, the observed changes in temperature were significantly robust and promise increasing signal patterns in all time scales.

Keywords: Mean temperature, Pakistan, Trends, Anomaly, Climatology.

1. Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (AR6) revealed an increase in global surface temperature of 0.8–1.3 °C from 1850–1900 to 2010–2019, with the best estimate of 1.07 °C (IPCC, 2021). In recent decades (1979–2010), a significant increase in the global surface temperature (> 0.17 °C/decade) has been observed, compared with the 0.07 °C/decade trend for 1901–2010. Northern/southern hemispheric trends of 0.08/0.07 °C/decade for 1901–2010 and 0.24/0.10 °C/decade for 1979–2010 have been recorded (Morice et al., 2012). Noticeable changes in the global average temperature have been observed in the past (Easterling et al., 2000; Fowler & Archer, 2006; Guan et al., 2019), and they have had disastrous effects on human well-being, such as the intensified occurrence of drought and flooding (Alexander, 2016; IPCC, 2013). In general, climate change has steadily impacted global environments, ecology, hydrology, agriculture, and economics in the form of compounded extremes such as drought and heat waves or temperature and precipitation extremes (Ahmed et al., 2019a, 2019b; Hood, 2007; IPCC, 2014; Perkins & Gibson, 2018).

Surface temperature is an integral part of climate variability and is used in local to global scale change analysis (Kothawale et al., 2010). Temperature has a critical direct or indirect effect on most biological and chemical reactions (Arora et al., 2003). Observationally, regional climate changes resulting in

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increased temperature affect diverse physical and biological systems globally (Root et al., 2003). Such changes include contraction of glaciers, melting of permafrost, earlier meltdown of river and lake ice (Mo et al., 2016), lengthening of growing seasons, earlier flowering in plants, the appearance of insects and diseases, and changes in habits and habitats of various fauna (Parmesan & Yohe, 2003).

Most developing nations are susceptible to the risks of climate change. The ability to cope with the likely impacts of climate change and its extreme events critically depends on governance and economic development (Hussain et al., 2019). Growing urbanization and populations under troubled economies are causing negative impacts on the natural environment. A decrease in vegetation cover and an increase in temperature exacerbate problems associated with climate change (McEvoy, 2007; Pingale et al., 2014; Siddique et al., 2020). The significant targets proposed by the Second Assessment Report (SAR) of the IPCC during the United Nations Framework Convention on Climate Change (UNFCCC), which identified two pathways, namely to limit global warming to 2 °C over pre-industrial levels, and a further downward trajectory to 1.5 °C over pre-industrial levels (UNFCCC, 2015), call for scientific assessment of the temperature evolution. An essential task for subsequent assessments has been to provide scientific information to help determine the quantified long-term goal for UNFCCC negotiations, i.e., political consensus based on scientific assessment (Dawson & Spannagle, 2020; UNFCCC, 2015).

Considerable progress has been made in detecting global and regional climate change. Paz et al. (2015) described the Middle East to southwest Asia region as water-stressed, societally vulnerable, and prone to severe droughts. Qian and Zhu (2001), Tang and Ren (2005), and Wen et al. (2006) observed noticeable changes in mean surface temperature over China in the 1920s to 1940s, similar to changes over the northern hemisphere and worldwide, with an increase of 0.50–0.80 °C. Climate-driven changes in mean temperature exhibited the highest robust warming for the observed records during winter and summer, with a similar projected pattern over the northwest region of China (Wang et al., 2017). Ayugi and Tan (2019) and Ayugi et al. (2021) observed positive changes in annual mean temperature trends over the East African region, with 0.021 °C/year for 1970–2014 and 0.09 °C/decade over Kenya for 1971–2010, whereas MAM and OND showed higher trends across Kenya. Zebaze et al. (2019) also reported significant warming, ranging from 0.1 to 2.2 °C over a 31-year study period (1975–2005) across all of Africa.

The South Asian region is among the most vulnerable regions to temperature change (Sivakumar & Stefanski, 2010). The economy in South Asia is mainly dependent on agriculture, which is linked to monsoon rains and winter temperatures (Goswami, 2005). Major river systems in South Asia (Ganges, Indus, Brahmaputra) are under threat due to rapid melting of Himalayan glaciers and extreme changes in precipitation variability and frequency, thus making the South Asian region more vulnerable (Wester et al., 2019). According to the IPCC (2007) and Iqbal and Zahid (2014), a temperature increase of more than 1.5 °C has been recorded in the South Asia region in recent decades, especially over the northern parts. The rapid melting of Himalayan glaciers and resultant variability in seasonal amounts and frequency of precipitation and the frequent occurrence of extreme events have damaged this region's economy, agriculture, livelihoods, infrastructure, and general welfare. Floods, epidemics, and droughts are common phenomena across the region (Sanjay et al., 2017; Wester et al., 2019).

According to Fang et al. (2017), Abbas et al. (2018), and Khan et al. (2019a), mean temperature reflects the average changes and trends in temperature extremes, i.e., T_{max} and T_{min}; this link can be helpful in understanding and predicting future trends of extreme weather events. Moreover, changes in the mean temperature trend arise due to changes in either the upper or lower thresholds of temperature, i.e. T^{max} or T_{min}, or both (Fang et al., 2017). Recently, Almazroui et al. (2020) reported an annual mean temperature range of –6 °C to 30 °C over South Asia during 1995–2014, with the highest record over the southwestern parts of the subcontinent. The lowest annual mean temperatures were observed over the Himalayan region in winters. Kothawale and Rupa Kumar (2005), Kothawale et al. (2010), and Srivastava et al. (2017) reported a temperature increase of about 0.22 °C per decade over northern, central, and eastern/northeastern India for the period 1971–2007, with pronounced warming trends in mean temperature in the winter and monsoon seasons. Pant and Kumar (1997) observed a significant warming trend of 0.57 °C/century over the years 1881–1997, with higher upward trends in the post-monsoon and winter seasons. Hingane et al. (1985) noted an increase (0.4 °C/century) in the surface temperature in the Western Himalayas, northwest, northeast, north central, east coast, west coast, and interior peninsula in the last decades. Tabari et al. (2011) observed significant positive trends (0.412, 0.45 °C/decade) in annual mean temperature over the west, south, and southwest of Iran from 1966 to 2005. Zarenistanak et al. (2014) reported a significant increase in temperature during summer and spring seasons over southwest Iran from 1950 to 2007. These and many other findings over the globe and South Asia overall clearly show the changes in temperature magnitude, variability, and distributions at varying timescales.

Pakistan is a focus of research on climate variability because climate change has severe impacts on Pakistan. McSweeney et al. (2008) observed lower annual mean temperature (< 0 °C) over the northern region than the southern region (20–25 °C) in summer. Del Río et al. (2013) observed increasing seasonal and annual mean temperatures (0.036 °C/year) across the country. Sajjad and Ghaffar (2019) observed a decrease in the minimum temperature over the northern region and a significant increase in the mean maximum temperature in the southern region during 1960–2013. Iqbal et al. (2016) observed the lowest annual temperatures over the northern Himalayan region and highest in the southeastern region for 1952–2009. Khan et al. (2019a) observed higher warming rates over the southern region during 1960–2013, and cold wave counts were observed over the northern region. The abovementioned studies and others have also observed a rise in past mean temperature at various spatiotemporal regions over Pakistan (Adnan et al., 2017; Afzaal & Haroon, 2009; Ahmad et al., 2009; Asmat & Athar, 2017; Del Río et al., 2013; Nawaz et al., 2019; Sadiq & Qureshi, 2010). Studies also acknowledge the implications of temperature change for agriculture (Adnan et al., 2017), hydrology (Fatima et al., 2020), the economy (Rasul et al., 2012), environment (Khatoon & Ali, 2004), and public welfare (Hussain et al., 2018) in Pakistan.

Several gaps, including a lack of complete datasets, limited seasons, lack of subregional studies, and the period under study, constitute the main weaknesses of many previous studies. Therefore, this study aims to document recent past annual and seasonal surface mean temperature change and variability (climatology, trends, and anomalies) over Pakistan over two subregions (Asmat & Athar, 2017) for the period 1970–2014. This is the first study to examine the subregional surface temperature variability over Pakistan in recent times. In addition, the study is designed as a baseline for seasonal temperature variability over two subregions of Pakistan in recent years.

This remainder of the paper is structured as follows. A description of the study area is given in Sect. 2, details of the datasets are described in Sect. 3, and the methods are given in Sect. 4. The results are presented in Sect. 5, followed by a discussion of the results in Sect. 6. Section 7 presents the conclusions of the study.

2. *Study Area Features*

Pakistan is a South Asian country with the geographical coordinates 23°–37.5° N latitude and 61°–78° E longitude covering an area of around 880,940 km^2 (Asmat & Athar, 2017). The altitude increases from south to north, with southern regions marked by lower elevations (0 m near the sea line) and northern regions showing higher elevations such as the Himalayan peaks (Khan et al., 2019c). Climatologically, most parts are arid (southern regions) and semiarid (central Punjab plains and north), characterized by hot summers and cold winters across the country (Hussain & Lee, 2009). Based on temperature distribution, the climate is generally classified into four seasons, namely (i) cold and dry winter (December–February), (ii) hot and dry spring (March–May), (iii) rainy monsoon summer (June–August), and (iv) autumn (September–November), where the onset and duration varies according to location. The temperature over the northern regions ranges from −13.0 °C in winter (minimum) to 19.5 °C in summer (maximum). Over the southern half, a minimum (winter) temperature of 13.2 °C and a maximum (summer) temperature of 34.8° have been observed over the years (Ahmed et al., 2014; Khan et al., 2019b, 2019c). For in-depth analysis, the whole study area is further divided into two subregions (Fig. 1), north and south, consistent with temperature and precipitation regimes. Northern Pakistan lies at the coordinates 30.25° N–37.20° N latitude and 66° E–78° E longitude, while the southern subregion is located at the coordinates 23.40° N–30.25° N latitude and 60.750° E–74.5° E longitude following Asmat and Athar (2017) and Asmat et al. (2018).

3. Datasets

3.1. Climate Research Unit (CRU) Dataset

For this study, a monthly surface mean temperature high-resolution gridded dataset from the Climatic Research Unit (0.5° × 0.5° resolution) for 1970–2014 was acquired for seasonal and annual spatiotemporal analysis. The CRU datasets were created by the Climate Research Unit of the School of Environmental Sciences at the University of East Anglia (Norwich, England). The CRU TS4.04 data were produced using angular-distance weighting (ADW) interpolation. The CRU TS4.04 data are monthly gridded fields based on monthly observational data calculated from daily or sub-daily data by the National Meteorological Services and other external agents (Harris et al., 2014). Studies of temperature over Pakistan (Afzaal & Haroon, 2009; Asmat & Athar, 2017) have successfully utilized the CRU temperature dataset. The seasonal and annual climatology and trend analysis was determined for the entire country and both the northern and southern regions.

4. Methods

The CRU dataset was first processed at the seasonal and annual scale for climatology, trends, and

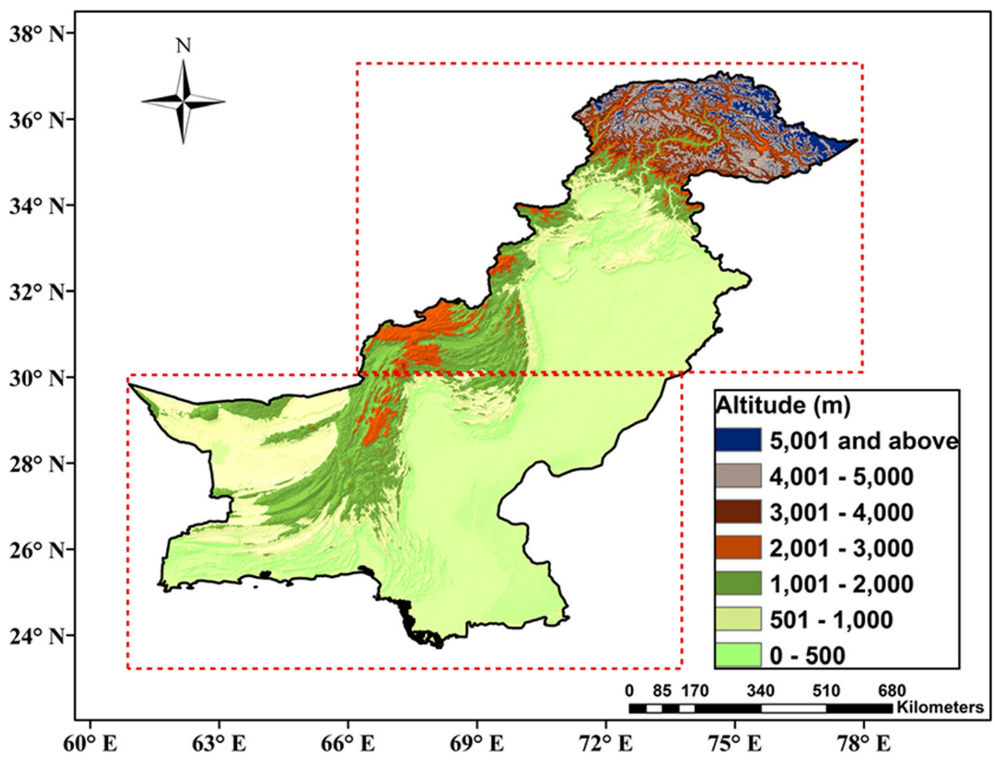


Figure 1
Topographical (m) map of the study area showing the latitudes and longitudes of the country. The two boxes inside the dashed lines represent the two subregions of Pakistan as upper/northern and lower/southern Pakistan

anomalies over the entire country and delineated subregions for the period 1970–2014 following Asmat et al. (2018). For example, the extreme northern region of the country is dominated by humid to arid climate, while the southern regions are dominated by continental and coastal climate (Farooqi et al., 2005). The seasons were defined as winter (December–February), spring (March–May), summer (June–August), and autumn (September–November) following Fowler et al., (2006), Asmat et al. (2018), and Khan et al. (2019c).

4.1. Mann–Kendall Trend Test

The Mann–Kendall and sequential Mann–Kendall (SQMK) trend tests were applied on seasonal and annual time series to delineate changes in temperature. The Mann–Kendall trend is a non-parametric test which gives correct trend estimates for datasets with outliers (Kendall, 1975; Mann, 1945). The SQMK has been used in many climatological studies (Ahmad et al., 2015; Ayugi & Tan, 2019; Ayugi et al., 2018; Iqbal & Athar, 2018; Khosravi et al., 2017; Latif et al., 2017) across the globe. Mathematically, the standardized MK test can be written following equations given by Kendall (1975) and Mann (1945) as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(xj - xi), \tag{1}$$

where $x1, x2, \ldots, xn$ represent the n data points, and xj represents the data point at jth time. A high positive S indicates an increasing trend, while a low S value shows a decreasing trend, i.e.

$$\operatorname{sgn}(xj - xi) = \begin{Bmatrix} for(xj - xi) > 0 \\ for(xj - xi) = 0 \\ for(xj - xi) < 1 \end{Bmatrix}, \tag{2}$$

where xj and xi are the time series observations, and n is the length of the time series. When $n \geq 10$, S is approximately independently distributed data with mean of 0 and variance given by

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18}, \tag{3}$$

where n is the number of data points, m is the number of tied groups (sets of sample data having similar values), and t_i is the number of data points in the ith group. The MK test statistic, Z, is computed as

$$Z = \begin{Bmatrix} \frac{S-1}{\sqrt{\operatorname{Var}(S)}} \\ 0 \\ \frac{S+1}{\sqrt{\operatorname{Var}(S)}} \end{Bmatrix} \begin{Bmatrix} if & S > 0 \\ if & S = 0 \\ if & S < 0 \end{Bmatrix}. \tag{4}$$

If the Z values remain beyond the confidence interval of ± 1.96, the trend is statistically significant at the 95% confidence level. The trend is considered decreasing if Z is negative and increasing if Z is positive. In this study, this method was applied on seasonal and annual time series data. The seasonal and annual temporal datasets were treated for the MK test at a 95% confidence level.

4.2. Sequential Mann–Kendall Trend Test

The SQMK test detects the abrupt changes and new trends in time series data (Sneyers, 1990) and has been successfully employed for temperature trends in and around Pakistan (Ayugi & Tan, 2019; Chatterjee et al., 2014; Ullah et al., 2019a). Such abrupt changes in trends are estimated by progressive (u) and retrograde (u') series. u values are ordered from first to last while u' values are ordered from last to first values of time series. The SQMK test is computed using ranked values (y_i) of the original values $x_1, x_2 \ldots x_n$. The y_i values are compared with y_j ($j = 1 \ldots i–1$), where cases with $y_i > y_j$ are counted and denoted by n_i. The test statistic t_i is calculated as (Mann, 1945; Sneyers, 1990):

$$t_i = \sum_{1}^{i} ni. \tag{5}$$

The mean and variance of the t_i statistic are then computed as

$$E(t_{i)} = \frac{t(t-1)}{4}, \tag{6}$$

$$\mathrm{Var}(t_i) = \frac{i(i-1)(2i+5)}{72}. \quad (7)$$

For each of the test statistic variables *ti*, the sequential values for the standardized variable *u(ti)* and *u′(ti)*) are calculated as

$$u(t_i) = \frac{t_i - E(t_i)}{\sqrt{\mathrm{Var}}(t_i)}. \quad (8)$$

The progressive sequential statistics *u(ti)* values are calculated using original values from first to last, while retrograde sequential statistics *u′(ti)* values are calculated using the last to first values of series. When plotted, the intersection of *u(ti)* and *u′(ti)* show the potential trend turning point. If the intersection occurs at a threshold interval of ±1.96 (95% confidence level) of the *Z* statistic, the trend turning point is considered significant. Decreasing values of *u(ti)* and *u′(ti)* indicate a negative trend, while increasing values represent a positive trend in the time series. When the magnitude of at least one of the values of the reduced variable is greater than 1.96, the beginning of a new trend is considered. In the sequential MK graph, the confidence limits for standard normal *Z* values are α = 5%. Consequently, the upper and lower confidence limits are −1.96 and 1.96, respectively. When the progressive MK values cross either confidence limit, this indicates a new trend beginning at the 95% confidence level. Annual and seasonal time series are treated at the 95% confidence level to detect abrupt changes.

4.3. Least Squares Linear Regression

Trend analysis with a robust, slope-based test, namely iteratively reweighted least-squares regression (IRLS) (Welsch, 1977), is used for spatial trend detection of seasonal and interannual mean temperature. This technique is more robust for evaluating data influenced by outliers, as the results are not influenced by outliers (Basha et al., 2017). The significance of trends at each grid box is estimated, and the grids passing the 95% confidence level are considered significant.

5. Results and Discussion

5.1. Annual Temperature Variability over Pakistan

The preliminary analysis of this study included the computation of annual mean, skewness, and coefficient of kurtosis, as given in Table 1. Over all of

Table 1

Statistical details of monthly, seasonal, and interannual mean temperature over subregions of Pakistan for 1970–2014

Month/Season	All-Pakistan					Northern Pakistan					Southern Pakistan				
	μ	SD	Skw	Kts	CV	μ	SD	Skw	Kts	CV	μ	SD	Skw	Kts	CV
Jan	7.4	1.0	−0.5	0.2	13.0	0.02	0.9	−0.1	−0.3	4740.6	14.6	0.8	−0.3	0.006	5.6
Feb	9.6	1.5	−0.5	1.1	15.4	1.8	1.5	−0.2	0.6	81.6	17.0	1.3	−0.3	1.1	7.9
Mar	14.9	1.4	0.6	0.01	9.1	7.0	1.5	0.6	0.01	21.2	22.3	1.3	0.6	−0.1	5.8
Apr	20.7	1.1	−0.04	−0.2	5.2	12.9	1.3	0.006	−0.4	9.8	27.6	1.1	−0.3	0.1	3.9
May	24.9	1.1	−0.2	−0.4	4.2	17.1	1.4	−0.01	−0.5	8.1	31.4	0.9	−0.2	−0.2	2.7
Jun	27.5	0.5	0.3	0.1	1.7	20.9	0.7	0.3	−0.7	3.2	32.7	0.5	0.1	0.7	1.5
Jul	27.4	0.4	−0.01	−0.5	1.5	22.1	0.5	0.01	−0.5	2.2	31.4	0.5	−0.2	−0.4	1.5
Aug	26.2	0.5	0.2	0.3	2.0	21.3	0.5	0.2	0.1	2.3	30.1	0.5	0.5	0.7	1.7
Sep	23.6	0.6	−0.1	0.3	2.6	18.2	0.7	−0.02	0.03	3.6	28.7	0.6	−0.04	−0.6	2.2
Oct	19.5	0.8	0.2	−0.8	4.3	13.1	0.9	0.1	−1.0	6.7	25.9	0.9	−0.01	−0.6	3.4
Nov	14.1	0.7	−0.5	0.4	5.3	7.2	0.7	−0.6	0.005	10.3	20.9	0.8	0.03	0.02	3.9
Dec	9.4	0.8	−0.2	−0.9	8.9	2.4	0.8	−0.4	−0.4	34.5	16.3	0.8	0.1	−0.1	5.0
DJF	8.78	0.8	−0.4	−0.4	9.1	1.4	0.8	−0.3	−0.2	53.8	16.0	0.7	−0.2	−0.2	4.7
MAM	20.2	0.9	0.03	−0.5	4.5	12.3	1.0	0.05	−0.9	8.4	27.1	0.9	0.04	0.2	3.2
JJA	27.0	0.3	0.2	0.5	1.3	21.4	0.4	−0.1	−0.4	1.8	31.4	0.4	0.3	0.4	1.1
SON	19.1	0.5	−0.04	−0.7	2.6	12.8	0.5	0.04	−0.5	3.9	25.2	0.6	−0.1	−0.9	2.2
Annual	18.8	0.5	−0.1	−0.7	2.6	12.0	0.5	−0.2	−1.1	4.0	24.9	0.5	0.1	−1.0	1.9

All analyses were carried out at a 95% confidence level

μ = population mean, *SD* = standard deviation, *Skw* = skewness, *Kts* = kurtosis, *CV* = coefficient of variation

Pakistan, mean temperatures of 8.78 °C, 20.2 °C, 27.0 °C, 19.1 °C, and 18.8 °C are observed for DJF, MAM, JJA, SON, and annual timescales. Over northern Pakistan, seasonal mean temperatures of 1.4 °C, 12.3 °C, 21.4 °C, 12.8 °C, and 12.0 °C are observed for DJF, MAM, JJA, SON, and annual timescales. The MAM and DJF season display a coherent distribution of temperature over the northern region. Similarly, over the southern subregion, the seasonal mean temperature distribution of 16.0 °C, 27.1 °C, 31.4 °C, 25.2 °C, and 24.9 °C during DJF, MAM, JJA, SON, and annual timescales is delineated for 1970–2014. The MAM and DJF across all three regions displayed lower variability in skewness and kurtosis and higher coefficient of variation, thus showing high spatial coherence in temperature distribution and variability.

Figure 2 shows the mean monthly surface temperature variation across the entire country (Fig. 2a) and the northern (Fig. 2b) and southern (Fig. 2c) subregions of Pakistan for 1970–2014. For the country overall (Fig. 2a), the highest values (nearly 27 °C) are found in JJA, while the lowest (7–9 °C) are observed in December and Jan. Over the northern region (Fig. 2b), the highest temperature is observed during JJA (20–22 °C) and the lowest in DJF (0–3 °C) months.

The southern region (Fig. 2c) exhibits the highest temperatures during the months of May–July (30–33 °C) and the lowest during December–February (14–17 °C). Across all regions, the highest temperatures annually are exhibited in June–August, and the lowest in December–February. Ullah et al. (2019a) reported that January was the coldest month

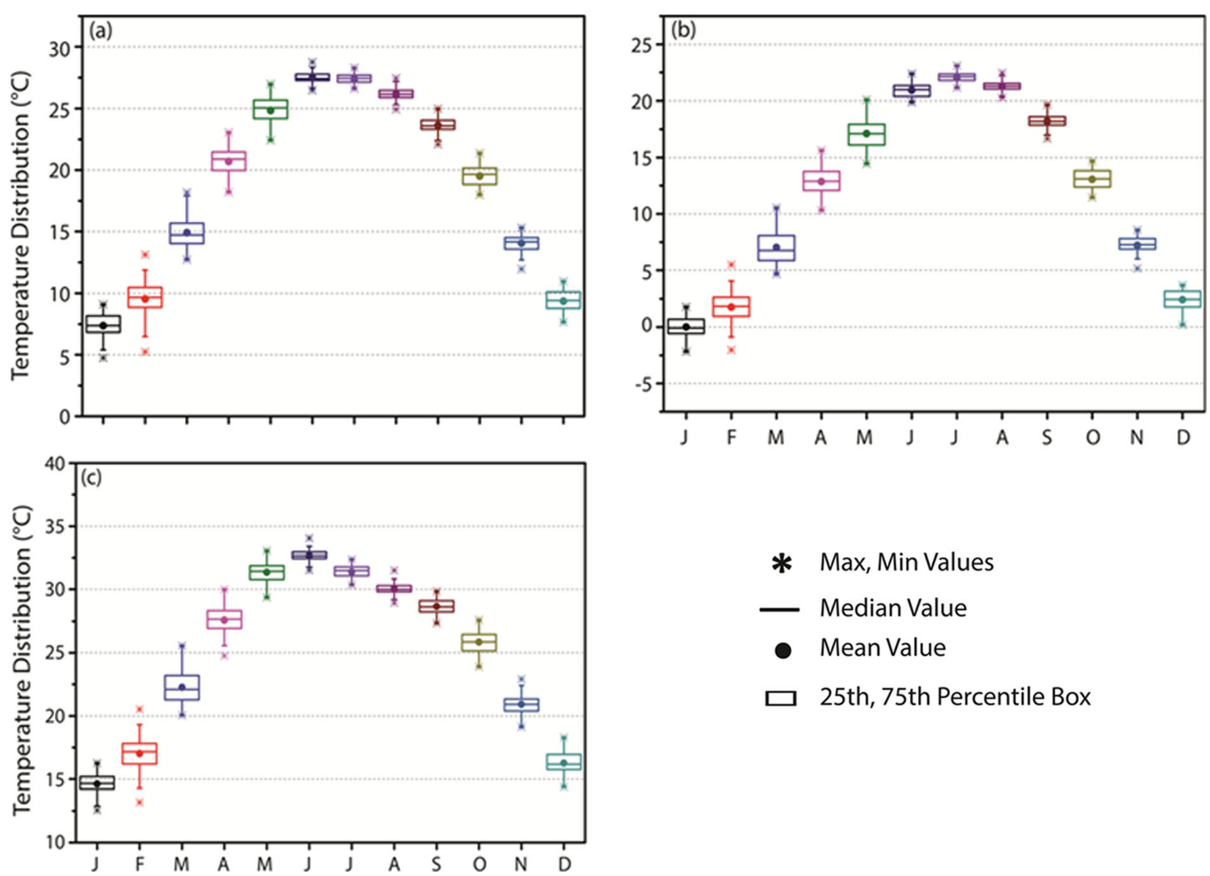


Figure 2
Mean annual temperature cycle over all of Pakistan (**a**), northern Pakistan (**b**), and southern Pakistan (**c**) for the years 1970–2014. Boxes and whiskers show the mean (line), median (dot), range (SD), and outliers (asterisk) of time series

(10 °C) and July (30 °C) the hottest month for long-term monthly means. Similarly, Asmat and Athar (2017) observed annual mean temperature (standard deviation) of 26.90 °C (0.33), 24.25 °C (0.43), and 29.55 °C (0.31) over the whole, northern, and southern Pakistan using the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) dataset. Furthermore, for the cold months of December, January, and February, the mean temperature remained below 20 °C, while March, April, and May exhibited a mean temperature of 28.16 °C. June, July, and August were found to be the hottest months, with a mean temperature of 33.60 °C. In the north (south), December, January, and February exhibited mean temperature of 7 °C (15 °C), while in June, July, and August, the temperature was quite high (32.52 °C) over the southern region.

5.2. *Seasonal and Annual Climatology*

The seasonal and annual mean temperature distribution over Pakistan for 1970–2014 is presented in Fig. 3. The DJF (winter) season (Fig. 3a) shows a temperature range of −15 °C to 20 °C across the country, with higher values (0–20 °C) over the southern and lower values (−15 to 15 °C) over the northern region. The MAM (spring) shows temperature distribution (Fig. 3b) between 0 and 30 °C across the country, with higher values over the southern region (10–30 °C) and lower values (0–30 °C) over the northern region. JJA (summer) exhibits (Fig. 3c) a distribution of 5–40 °C over the country, with a higher magnitude (20–40 °C) over the southern region and lower magnitude (10–35 °C) over the northern region. The SON (autumn) shows a distribution of −5 to 30 °C across the country (Fig. 3d), with a higher range (5–30 °C) over the southern region and lower range (−5 to 35 °C) over the northern region. The interannual (Fig. 3e) temperature ranges from −5 to 30 °C over the country, with a lower scale over the northern region (−5 to 30 °C) and a higher scale over the southern region (5 to 30 °C). Overall, JJA exhibits the strongest temperature distribution and DJF shows the lowest magnitudes among all seasons.

The southern region exhibits higher temperature than the northern region across all timescales. Sarfaraz et al. (2014) reported mean annual temperature of 11–30 °C over the north and 24–30 °C in the south during 1981–2010. Further, the northern (southern) parts recorded mean temperatures of −1 to 5 °C (11–18 °C) in winter, 5–11 °C (24–30 °C) in spring, 11–20 °C (24–30 °C) in summer, and 5–11 °C (30–37 °C) in autumn. McSweeney et al. (2008) observed temperatures of 15 °C (20–25 °C)

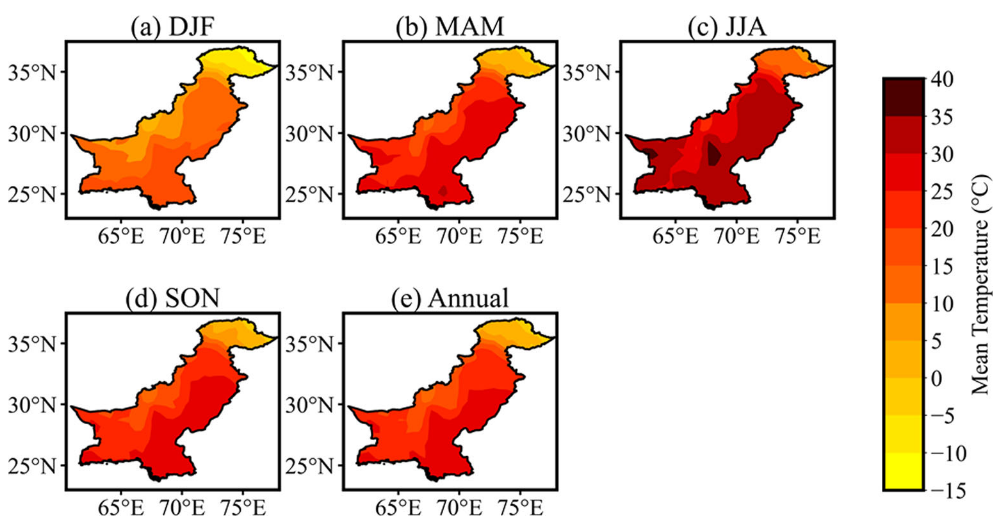


Figure 3
Spatial distribution of mean seasonal and annual temperature over Pakistan for the period 1970–2014

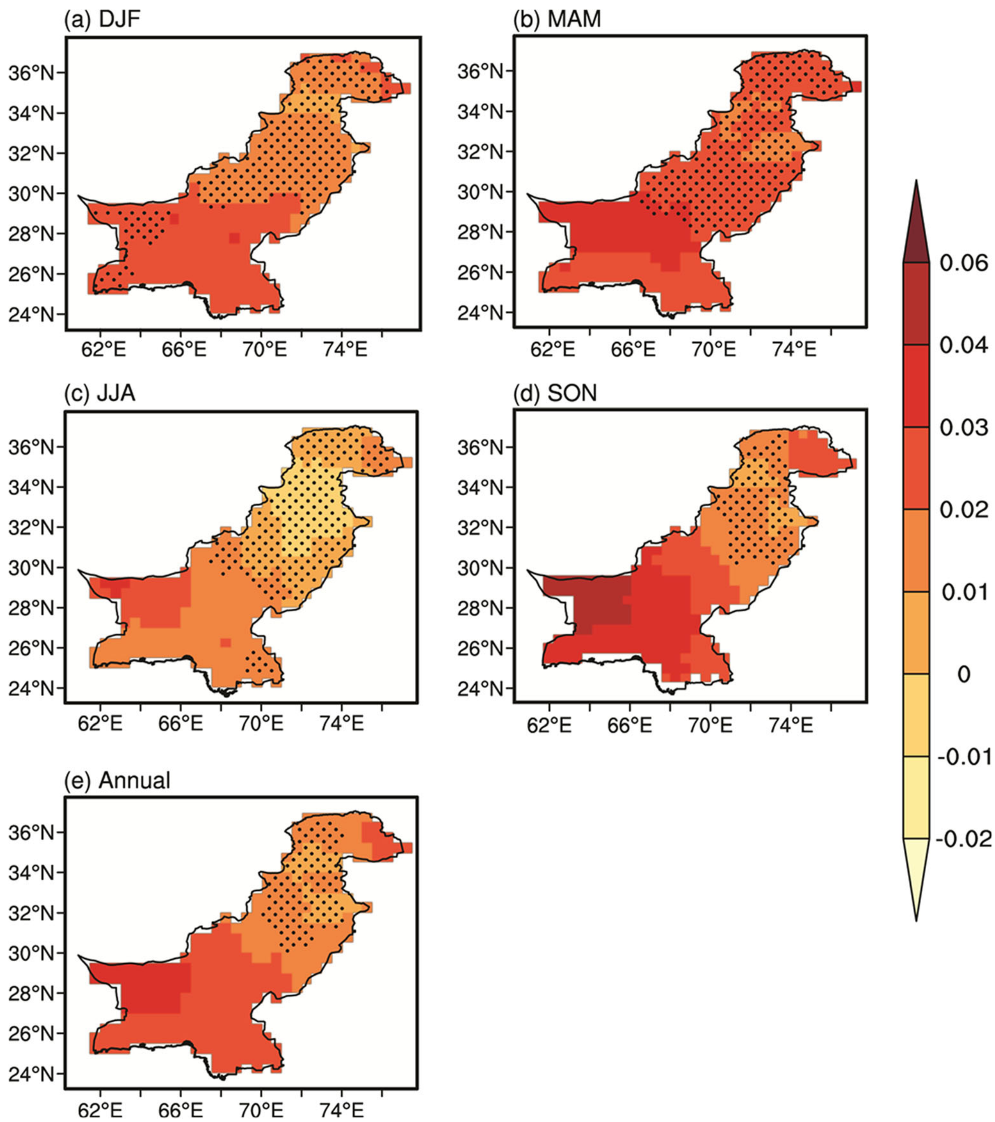


Figure 4
Spatial distribution of linear trends for mean seasonal and annual temperature across Pakistan during 1970–2014 timescale. Hatch marks show the significance of trends at the 95% confidence level

over the northern (southern) regions in summer and 35 °C (20–25 °C) in winter. A study by Asmat and Athar (2017) noted two temperature regimes, with a higher-temperature band (of up to 35 °C) extending in the east–west direction over southern Pakistan, and a second lower-temperature belt spanning northern Pakistan. The average annual temperature over all of Pakistan was about 26.90 °C. Similarly, Athar and Latif (2018) identified DJF minimum to maximum temperature of −15 to 25 °C over northern Pakistan. In MAM, the minimum and maximum temperatures over the southern region were smaller (∼25 to 30 °C) than those of DJF (∼40 °C). During JJA, an average temperature of ∼35 °C was observed over southern Pakistan. This band approached the north, thereby increasing the temperature in the north, and retreated during SON. A study by Ullah et al. (2019a) for temperature extremes (T_{max} and T_{min}) over Pakistan also exhibited positive trends at seasonal and interannual scales, with MAM, DJF, and SON showing higher positive trends over the north, northwestern, and southeastern regions.

5.3. Temperature Trends Distribution

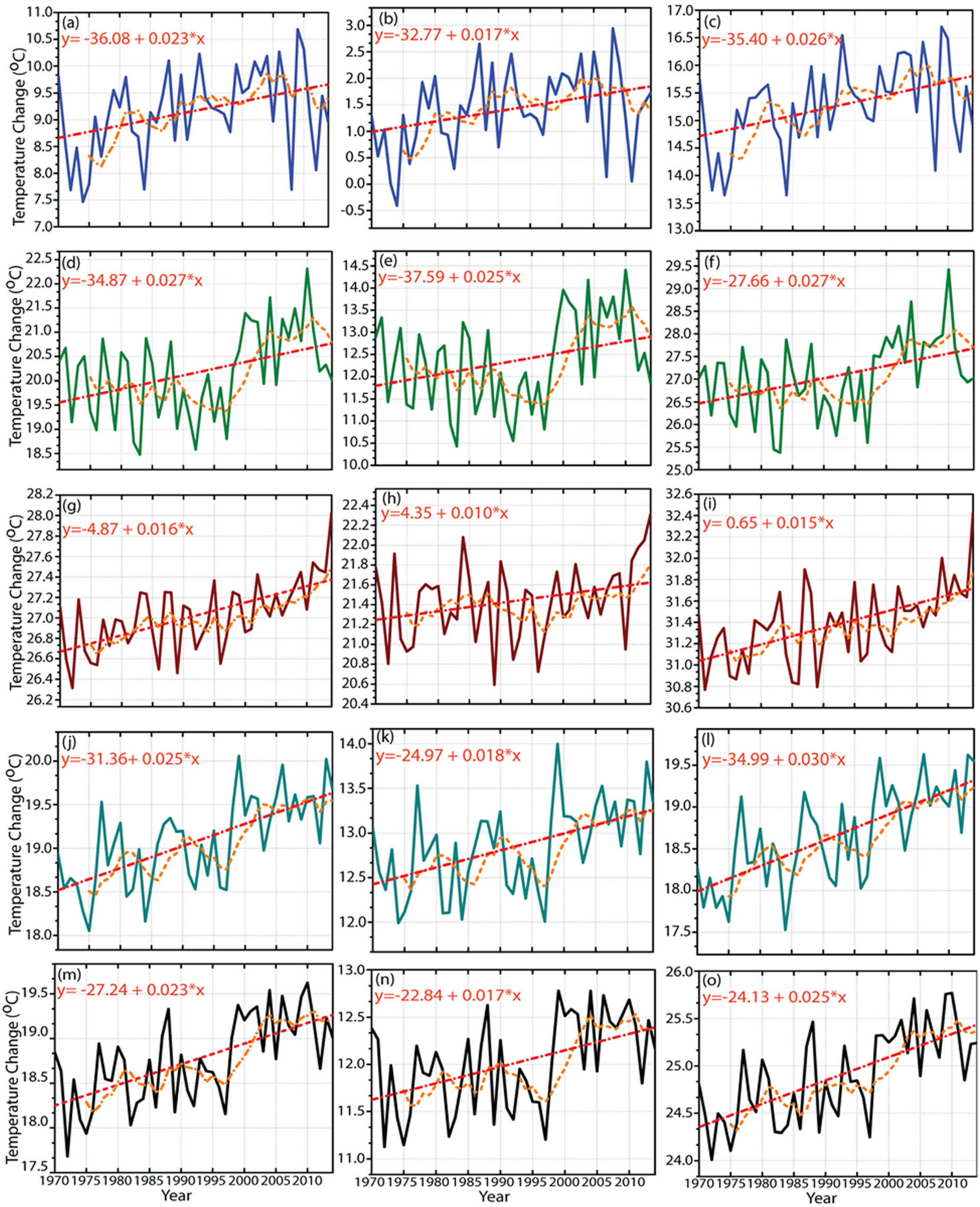
The seasonal and annual temperature trend distributions over all of Pakistan and the subregions for 1970–2014 are shown in Fig. 4. The DJF spatial trends exhibited an increase (Fig. 4a) in temperature across the country (0–0.04 °C/year), with significant values in the northern region and parts of the south. Del Río et al. (2013) observed an increase in DJF temperature over Pakistan by around 0.05 °C/year on average from 1952 to 2009. A rise in mean temperature at the national, regional, or local time scales in the DJF was also observed by Hussain et al. (2005) and Islam et al. (2009). During the MAM months (Fig. 4b), significant positive trends in temperature (0.01–0.04 °C/year) were observed across most of the country, with higher (0.02–0.04 °C/year) magnitude over the southern region than the northern region (0.1–0.4 °C/year). Sheikh et al. (2009) and Del Río et al. (2013) reported an increase in MAM temperature by 0.05 °C/year on average over Pakistan, with small negative trends over specific stations. In JJA, positive (0.0–0.03 °C/year) trends were observed over most of the study area (Fig. 4c), with the exception being parts of the northern region showing negative trends (0.0 to −0.01 °C/year).

The southern region showed stronger trends (0.01–0.03 °C/year) during the season. Similar results with negative trends over several other parts and over northern Pakistan in JJA were reported by Cheema et al. (2006), Chaudhry et al. (2009), and Del Río et al. (2013). The SON season (Fig. 4d) showed a positive trend (0.0–0.06 °C/year) across the country, with the southern region showing stronger positive trends (0.02–0.06 °C/year) than the northern region (0.01–0.03 °C/year). McSweeney et al. (2008) observed the lowest seasonal positive trend (0.016 °C/year) in the SON season over Pakistan.

The interannual trend distribution showed higher (Fig. 4e) positive trends across the country (0.0–0.04 °C/year), and the southern region exhibited stronger trends (0.02–0.04 °C/year) than the northern region (0.0–0.02 °C/year). Del Río et al. (2013) measured an interannual temperature upsurge of 0.036 °C/year on average for 1951–2009. Chaudhry et al. (2009) and Sheikh et al. (2009) also noted an increase of 0.24 °C/decade in mean annual temperature over Pakistan during 1960–2007, and greater than 0.06 °C/decade between 1901 and 2000. Afzaal and Haroon (2009) observed an increase in annual mean temperature at a rate of 0.06 °C/decade, and Chaudhry et al. (2009) reported an increase of 0.53 °C/decade during 1901–2000. Farooqi et al. (2005) observed an annual temperature increase of 0.6–1 °C over coastal areas of Pakistan since the early 1900s. Sajjad et al. (2009) observed an increase of 2.25 °C, 0.3 °C, and 1.95 °C in annual temperature for the coastal city of Karachi for 1947–2005, 1947–1975, and 1976–2005, respectively, while Sadiq and Qureshi (2010) reported a temperature increase of 0.040 °C/year to 0.065 °C/year over extreme northern parts of Pakistan.

During all seasons, the southern region displays a stronger warming trends than over the northern region, with the MAM displaying the highest warming trend, followed by DJF, SON, and JJA seasons. Ullah et al. (2019a) observed significant changes in maximum (minimum) temperature trend of 0.22 (0.33), 0.37 (0.39), 0.20 (0.25), 0.23 (0.27), and 0.31 (0.36) °C/decade in winter, spring, summer, autumn, and annual time scales over Pakistan, respectively. The current outputs for seasonal and annual trend patterns match those of many studies conducted over Pakistan (Afzaal & Haroon, 2009; Ahmad et al., 2009; Asmat & Athar, 2017; Del Río et al., 2013; Khan et al., 2019a; McSweeney et al., 2008; Nawaz et al., 2019; Sadiq & Qureshi, 2010), implying that temperature has increased in the past on annual and seasonal scales.

Figure 5 ▶
Linear trends and 5-year moving average of mean seasonal (first four rows) and annual (last row) temperature over all of Pakistan (**a**, **d**, **g**, **j**, **m**) and northern Pakistan (**b**, **e**, **h**, **k**, **n**) and southern Pakistan (**c**, **f**, **i**, **l**, **o**) subregions for 1970–2014. The red dashed line represents a linear trend with values shown in the top left corner, while the orange dashed line indicates the 5-year moving average mean temperature over the period 1970–2014 for each region


(a)
y= -36.08 + 0.023*x
(b)
y=-32.77 + 0.017*x
(c)
y=-35.40 + 0.026*x
(d)
y=-34.87 + 0.027*x
(e)
y=-37.59 + 0.025*x
(f)
y=-27.66 + 0.027*x
(g)
y=-4.87 + 0.016*x
(h)
y=4.35 + 0.010*x
(i)
y= 0.65 + 0.015*x
(j)
y=-31.36+ 0.025*x
(k)
y=-24.97 + 0.018*x
(l)
y=-34.99 + 0.030*x
(m)
y= -27.24 + 0.023*x
(n)
y=-22.84 + 0.017*x
(o)
y=-24.13 + 0.025*x
Temperature Change (°C)
Year
1970 1975 1980 1985 1990 1995 2000 2005 2010

5.4. Temporal Trends

The outputs for seasonal and annual temporal trends over Pakistan and its subregions during 1970–2014 are shown in Fig. 5. During DJF, the northern region (Fig. 5b) displayed lower (0.017 °C/year) trends than the southern region (0.026 °C/year; Fig. 5c) for 1970–2014. In MAM, the northern region (Fig. 5e) displayed a lower trend (0.025 °C/year) than the southern region (0.027 °C/year; Fig. 5f). During JJA, the northern region (Fig. 5h) exhibited a lower trend (0.010 °C/year) than the southern region (0.015 °C/year; Fig. 5i). Similarly, SON exhibited a smaller trend across the northern region (0.018 °C/year; Fig. 5k) than over the southern region (0.030 °C/year; Fig. 5l).

The interannual temperature trend over the northern region (Fig. 5n) exhibited lower magnitude (0.017 °C/year) than that over the southern region (0.025 °C/year; Fig. 5n). For the entire country, MAM (Fig. 5d) exhibited the highest (0.027 °C/year) positive trend, followed by SON (Fig. 5j) with 0.025 °C/year, and then DJF (Fig. 5a) and JJA (Fig. 5g) with 0.023 °C/year and 0.016 °C/year, respectively. Overall, the southern region exhibited higher positive trend changes than the northern region. Across the southern region, SON exhibited the highest positive trend and JJA showed the lowest. Over the northern region, MAM exhibited the highest increasing trends and JJA exhibited the lowest. Most of the trends across all spatiotemporal scales were found to be significantly increasing, the exception being the JJA trend over the northern region, which was found to be nonsignificant in nature (Table 2). These trends are similar to those reported by Saleem et al. (2021), with higher trends in MAM, followed by SON, DJF, and JJA for different temperature extremes. Athar and Latif (2018) reported similar trends in a study, with the highest temperature changes in MAM and JJA in southern Pakistan and further higher interannual variability in DJF and SON as compared with MAM and JJA. A significant decreasing (increasing) trend of −0.41 °C/year (0.33 °C/year) in northern (all) Pakistan in JJA with a value of 0.01 (0.02) was also observed. Although on an annual basis, a significant decreasing trend of about −0.35 °C/year was observed in northern Pakistan, Del Río et al. (2013) observed a strong increase in mean annual temperature (0.36 °C/decade) over Pakistan. This rise in temperature reflected the association between temperatures and certain teleconnection patterns and the influence of urbanization in the southern parts of the country.

Figure 6 ►
The abrupt changes reported in seasonal and annual mean temperature over all of Pakistan (**a**, **d**, **g**, **j**, **m**) and the northern Pakistan (**b**, **e**, **h**, **k**, **n**) and southern Pakistan (**c**, **f**, **i**, **l**, **o**) subregions for 1970–2014 timescale. The blue dashed line represents progressive time series, while the red dashed line represents the retrograde series of 1970–2014 mean temperatures over each mentioned region

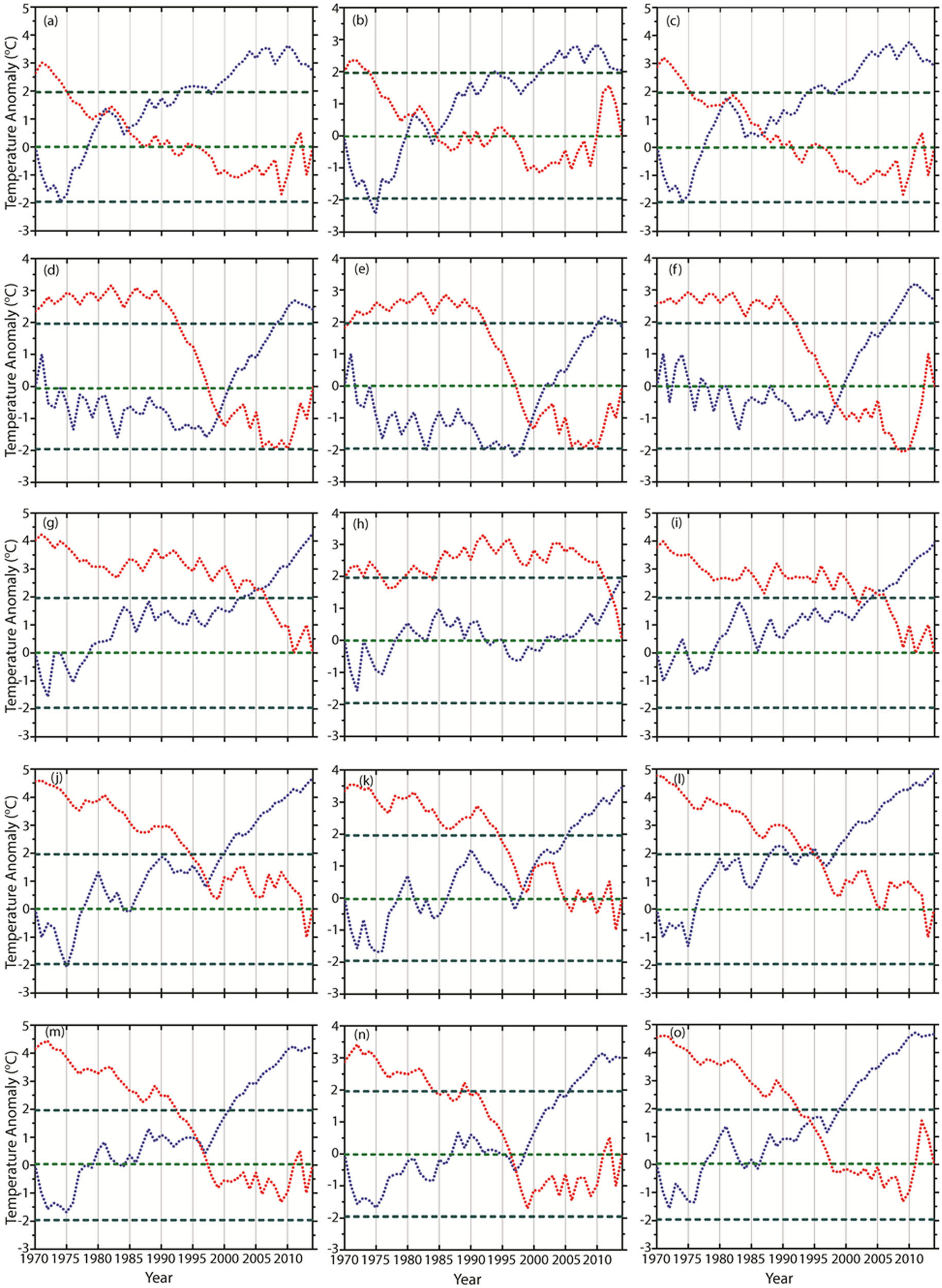
Table 2

The Mann–Kendall trend test results for seasonal and interannual mean temperature over all of Pakistan and its delineated subregions for the 1970–2014 timescale

Timescale	DJF		MAM		JJA		SON		Annual	
	MK Trend	▲/▼	MK Trend	▲/▼	MK Trend	▲/▼	MK Trend	▲/▼	MK Trend	▲/▼
All Pakistan										
1970–2014	0.025	▲ =	0.025	▲ =	0.016	▲ =	0.025	▲ =	0.023	▲ =
Northern Pakistan										
1970–2014	0.019	▲ =	0.024	▲ ≠	0.010	▲ ≠	0.019	▲ =	0.016	▲ =
Southern Pakistan										
1970–2014	0.028	▲ =	0.025	▲ =	0.015	▲ =	0.031	▲ =	0.025	▲ =

All analyses were carried out at 95% significance level

The ▲ = and ▼ = indicate the significant increasing and decreasing trend values for the time slices. The ▲ ≠ and ▼ ≠ signs indicate a nonsignificant increasing/decreasing trend. The individual ≠ sign indicates no trend detected. The significant and nonsignificant trends are analyzed at 95% confidence intervals


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
Temperature Anomaly (°C)
Year
1970 1975 1980 1985 1990 1995 2000 2005 2010

5.5. Abrupt Changes in Trends

The abrupt change in trends observed over all of Pakistan and its two subregions (northern, southern) is presented in Fig. 6. In SQMK trend shift detection, the intersection of u (progressive) and u' (retrograde) curves locate the approximate potential trend change point. If the intersection of u and u' occurs at 1.96 (95% confidence level) of the normalized Z statistic, one can infer a detectable change at that point in the time series. Also, when the progressive MK values exceed any of the confidence limits, this indicates the beginning of a new trend. During DJF, trends over all of Pakistan and northern and southern Pakistan (Fig. 6a–c) show a negative direction for 1970–1975, then a significant positive shift in 1985 (all Pakistan and northern region) and 1987 (southern region), and a new positive trend beginning after 2000. In the MAM season, all Pakistan and the northern and southern regions displayed a significant negative shift in trends for the 1971–1998 timeline, and then exhibited a significant abrupt positive shift in 1998, 1999, and 1998, respectively (Fig. 6d–f). After 2005, a new trend beginning (positive and then negative shift) is also visible over the whole country and the northern region for the MAM.

Similarly, in the JJA season, all of Pakistan and the southern subregion displayed a continuous significant positive mutation in trends (Fig. 6g, i) for 1970–2005, and then a nonsignificant positive shift (as well as new positive trends) is visible in year 2001. Over the northern subregion (Fig. 6h), the JJA trend showed a significant upward change at 1975–1985 and 2006–2014, but a significant negative mutation was also visible for 1985–2000. The SON season displayed (Fig. 6j–l) a significant downward and then upward shift in 1970 and 1996. However, a major significant positive shift in SON was observed in 1996, with a new trend beginning in 2000 (entire country and southern region) and 2005 (northern region). The interannual trend shift detection over the three delineated regions exhibited a significant positive shift over all three regions (Fig. 6m–o) in 1997 (whole region and northern region) and 1994 (southern). Similarly, a new positive trend was reported in 2000 for the whole country and the southern region, and in 2005 for the northern region.

In conclusion, most seasons showed most of the abrupt changes across the whole study area between 1994 and 2005, the exception being DJF, where most of the abrupt changes occurred during 1980–1985. Similarly, across the northern region, most seasons exhibited most of the abrupt changes in trends between 1995 and 2013, while DJF exhibited most of its abrupt changes during 1980–1985. Over the southern region, MAM, JJA, and SON displayed most of the abrupt changes between 1994 and 2006, whereas DJF exhibited most of its abrupt changes between 1980 and 1987. Among seasons, MAM demonstrated the strongest abrupt shift, followed by DJF, annual, SON, and JJA across all regions. JJA is the only season across all regions with nonsignificant positive trend shift points observed outside the significance level, while the DJF season across all regions showed the greatest number (positive and negative both) of abrupt changes. The rapid change in climate indicates the transition of climate from one stable state to another (Shahin et al., 1993; Xu et al., 2018) under the influence of diverse factors. As a climatic system crosses the threshold level due to some external factors, a shift to a new state occurs at a rate determined by the climate system (Sonali & Nagesh Kumar, 2013).

5.6. Decadal Abnormalities in Temperature

The decadal anomalies in seasonal and annual temperature over Pakistan for the period 1970–2014 are displayed in Fig. 7. The DJF season changes show negative anomalies (−0.01 to −1.0 °C/decade) in the first and second decades (Fig. 7a, b) over most of Pakistan, the exception being positive changes over the extreme north in the second decade. However, in the third to fifth decades (Fig. 7c–e), positive changes (0.01–1.0 °C/decade) were observed across the country (except negative over extreme north). Malik et al. (2012) found similar results for DJF temperature anomalies over Pakistan, where the 2000–2009 decade represented the post-climate change scenario. In MAM, the first to third decades (Fig. 7f–h) exhibited negative (−0.01 to −0.80 °C/decade) anomalies (except positive across the northeast in the first decade), but the last two decades (Fig. 7i, j) showed positive anomalies (0.40–1.0 °C/

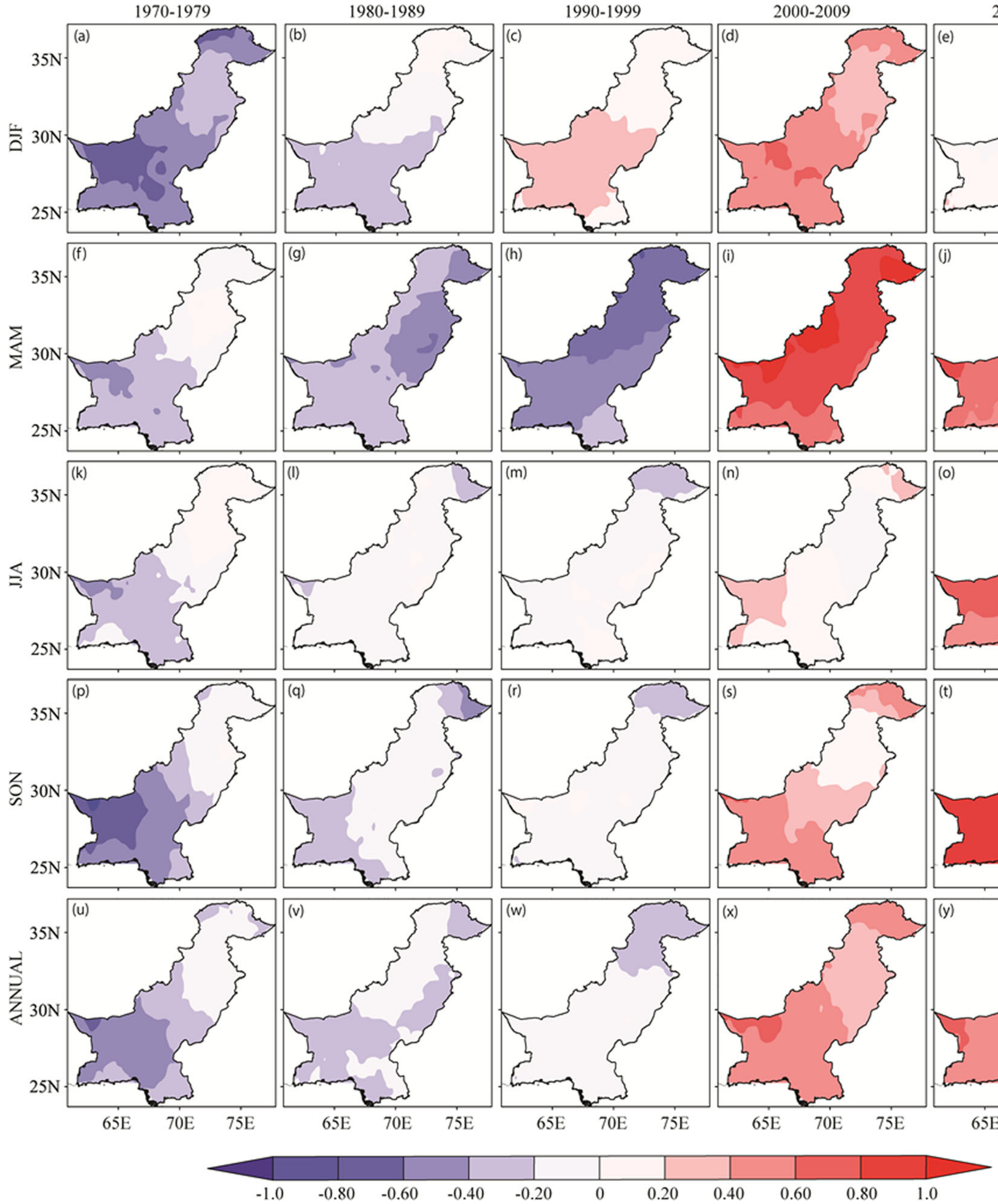


Figure 7
The spatial distribution of seasonal and annual mean temperature anomalies over the study area for 1970–1979, 1960–1989, 1990–1999, 2000–2009, and 2010–2014 timescales

decade). The JJA temperature in the first to third decades (Fig. 7k–m) showed negative anomalies (−0.01 to −0.60 °C/decade) across the country (except slight positive over the north in first decade).

In the last two decades (Fig. 7n, o), positive anomalies (0.01–0.80 °C/decade) were observed over the country. The SON season, during the first to third decades (Fig. 7p–r), exhibited negative anomalies (−0.01 to −1.0 °C/decade), but positive anomalies

(0.01–1.0 °C/decade) were exhibited in the last two (Fig. 7s, t) decades over the country. The interannual temperature in the first three decades (Fig. 7u–w) exhibited negative (−0.01 to −1.0 °C/decade) changes across the study area (except positive over the southeast in the third decade). In the last two decades (Fig. 7x, y), positive anomalies (0.20–0.80 °C/decade) were exhibited. In all time-scales, the first three decades (1970–1979, 1980–1989, and 1990–1999) exhibited strong negative anomalies across the country (except positive anomalies in DJF during 1990–1999). During the last decades (2000–2009 and 2010–2014), strong positive changes in temperature were exhibited across most of Pakistan. The seasonal and annual anomalies observed clearly indicate that the temperature across Pakistan has increased in recent decades, and this is in line with the above analysis and other studies mentioned in earlier sections.

6. *Discussion*

Time series analysis examines the temporal characteristics of a variable by detecting its significant characteristics including normality, persistence, trends, and change points. Trends identify gradual change occurring over a certain time span, while abrupt change point analysis shows the points of a series to a completely different regime. Normality, on the other hand, refers to the data distribution idealizing a normal distribution that helps in identifying dependent links between the successive members of a time series (Shahin et al., 1993; USEPA, 1996).

This study revealed seasonal spatiotemporal variability in mean surface temperature over subregions of Pakistan during 1970–2014. The mean climatology, trends, and anomaly analysis yielded positive changes in temperature across all spatiotemporal scales. Mean climatology exhibited a north (lower) and south (higher) temperature gradient at annual and seasonal scales, as also observed by Malik et al. (2012). Islam et al. (2009) observed a mean temperature change of 0.6 °C during 1900–2000, with 0.8 °C over the northern region and 0.6 °C over the southern region. The highest mean temperatures were exhibited in June–August and the lowest in December–February. The MAM exhibited the highest positive change trend in temperature, followed by SON, DJF, and JJA, over the entire country. Sadiq and Qureshi (2010) found an increase in the annual temperature of 0.040–0.065 °C/year over extreme northern Pakistan. Recent studies of seasonal and interannual temperature over Pakistan revealed that the temperature in the extreme north (over Himalayan regions) dropped below 0 °C in the winter months and that summer (May–September) was the warmest period over the north (> 30° N), where the temperature reaches 15 °C (Asmat & Athar, 2017; Farooqi et al., 2005; McSweeney et al., 2008). Most parts of Pakistan have an arid to semi-arid climate, with significant temporal and spatial variability under various climatic parameters (Chaudhry et al., 2009).

Topography has a strong influence on the surface temperature (Asmat & Athar, 2017). The phenomenon of elevation-dependent warming (Pepin et al., 2015; Rangwala et al., 2010; You et al., 2020) is established as a major factor for global warming at higher altitudes as a result of snow-albedo positive feedback (You et al., 2020). Following this, Fowler et al., (2006) observed a strong association between runoff (snowmelt water) and increased temperature over the Upper Indus Basin of Pakistan. Northern Pakistan is a mountainous region and is sensitive to climate change (Fowler & Archer, 2006; Malik et al., 2012; Ren et al. 2017; Khan et al., 2019a; Nawaz et al., 2019), with dominant humid to arid climate (Farooqi et al., 2005) regimes and mean annual temperatures ranging between below 0 to 20 °C (Ullah et al., 2019a).

In this study, the southern regions revealed the SON season as that with the highest positive trend, followed by DJF, MAM, and JJA. Farooqi et al. (2005), McSweeney et al. (2008), and Asmat and Athar (2017) reported the months of May–September as the warmest months, with the temperature reaching 35 °C in the south (< 30° N), while in the winter months, the temperature remained up to 20–25 °C in the low-lying south. Farooqi et al. (2005) and Sajjad et al. (2009) observed an increase in annual temperature for coastal regions of Pakistan from the early 1900s to 2005 at different scales. The southern region has a mostly arid environment, with the presence of vast deserts in the center, dry hilly terrains to the west, and warm coastal regions (Rasul et al., 2012) over the south. The central and central-eastern parts of Pakistan feature the Indus plains and their tropical climate, with mean annual temperature ranging from 21 to 25 °C. The coastal belt over the south is dominated by a coastal climate, with mean annual temperature ranging from 26 to 30 °C (Asmat & Athar, 2017; Farooqi et al., 2005; Ullah et al., 2019a).

Variability in global circulations with local topography affects the climate variability in Pakistan, evidenced by the strong effects of the North Atlantic Oscillation (NAO) and El Niño–Southern Oscillation (ENSO) global circulations on local and regional weather phenomena (Attada et al., 2019; Attada et al., 2019; Del Río et al., 2013). For example, low-level geopotential height was found to control the wet and dry conditions by regulating moisture transport from adjacent oceans to the region (Ain et al., 2020). Bollasina and Nigam (2011) observed that the thermal forcing and low-level northerlies (indirect) have a strong influence on deepening heat low during JJA and DJF over the Hindu Kush Mountains. Asmat et al. (2018) observed cold westerlies and northwesterlies over northern Pakistan during winter months and heat low, land–sea thermal gradient, and moisture flux as potential causes of warmer climate over southern areas in summer. Interestingly, large-scale circulations (Hadley cell, jet streams, storm tracks, planetary waves) have changed in recent decades under climate change (Molnos et al., 2017) or climate feedback.

The influence of greenhouse gas emissions under chaotic hydrocarbon use, disorganized industrialization and urbanization, massive transportation systems, ineffective waste management, massive land use changes, and other factors on climate is evident considering the rise in global and local temperatures (Hussain et al., 2019; IPCC, 2013; Rasul et al., 2008). The associated impacts may include changes in the frequency and nature of weather extremes and alterations of fertile habitats with repercussions for humans, biodiversity, and agriculture at large (Hood, 2007; Perugini et al., 2017). Most of the regions of Pakistan (particularly the southern region) are observed with rising temperatures, likely due in part to unplanned industrialization and transportation, land use change (Abbas, 2013), population pressure, vegetation loss, and pollution (aerosols and other chemical compounds), thus paving the way for heat waves, droughts, landslides, glacial lake outburst floods (GLOFs), flash floods, avalanches, and erosion (Haider & Adnan, 2014; Hussain et al., 2019; Khan, 2015; Rasul et al., 2012; Ullah et al., 2019b). The acute lack of awareness and knowledge regarding climate change, measures to counter it (mitigation and adaptation), and misconceptions and fallacies concerning the climate change phenomenon and its impacts is still prevalent among a large proportion of communities in Pakistan (Graffeo, 2017; Hussain et al., 2019).

The findings of this study, its consistency with previous studies, and possible reasons and associated adverse impacts discussed can be used as a baseline for tackling the climate change problem and devising a long-term plan for adaptation to future climate change in the study area. Further investigations into future scenarios of warming and mechanisms would better help in halting and coping with future warming and its adverse outcomes.

7. Conclusion

Seasonal and annual temperature changes provide the most important insights into climate change. Seasonal and annual temperatures exhibited diverse spatiotemporal variability over the study area during the period 1970–2014. A significant increase was seen at all timescales and spatial scales. In climatology (Fig. 3), JJA exhibited the highest temperature distribution (5 to $>$ 35 °C) and DJF the lowest ($-$15 °C to 20 °C).

The southern region exhibited higher temperatures than the northern region across all timescales. Overall (Table 1), the JJA season exhibited the highest (27 °C) mean temperature over the country, followed by MAM (20.2 °C), SON (19.1 °C), and DJF (8.8 °C); annual mean temperature was 18.8 °C. The southern region revealed higher mean temperatures in DJF, MAM, JJA, SON, and annual (16 °C, 27.1 °C, 31.4 °C, 25.2 °C, and 24.9 °C) timescales than the northern (1.4 °C, 12.3 °C, 21.4 °C, 12.8 °C, and 12.0 °C) region across all seasons and annual scale for 1970–2014.

Spatially, DJF (0–0.04 °C/year), MAM (0.1–0.06 °C/year), JJA (−0.01 to 0.03 °C/year), SON (0–0.06 °C/year), and annual (0.01–0.04 °C/year) showed positive trends across the study region (except negative trends in JJA over patches in the northern region) (Fig. 4). Trend magnitudes were higher over the south but nonsignificant, in contrast to the north. Temporally, MAM (Fig. 5d) exhibited the highest (0.027 °C/year) positive trends, followed by SON (Fig. 5j), DJF (Fig. 5a), and JJA (Fig. 5g) with 0.025 °C/year, 0.023 °C/year, and 0.016 °C/year, respectively, across the country. The increase in the annual trend over the whole country was 0.023 °C/year. Over the north, MAM (Fig. 5e) revealed the highest (0.025 °C/year) increase, followed by SON (Fig. 5k), DJF (Fig. 5b), and JJA (Fig. 5h), with 0.018 °C/year, 0.017 °C/year, and 0.010 °C/year, respectively, while the annual (Fig. 5n) scale displayed a positive trend of 0.017 °C/year. The southern region exhibited higher positive trends than the north. Across the south, SON (Fig. 5l) yielded the highest positive trend (0.030 °C /year), followed by MAM (Fig. 5f), DJF (Fig. 5c), and JJA (Fig. 5i), with values of 0.027 °C /year, 0.026 °C /year, and 0.015 °C/year, respectively. The annual increase observed across the south was 0.025 °C /year.

As shown in Fig. 6, the seasons overwhelmingly showed strong abrupt changes across the whole study area between 1994 and 2005, the exception being DJF, for which abrupt changes were observed during 1980–1985. Similarly, over the south, most seasons exhibited abrupt changes in trends during 1995–2013, while only DJF exhibited such changes in 1980–1985. In the southern region, MAM, JJA, and SON showed that abrupt changes occurred during the period 1994–2006, whereas DJF exhibited the most abrupt changes between 1980 and 1987. Across all spatiotemporal scales, MAM displayed the strongest abrupt shifts in magnitude, followed by DJF, annual, SON, and JJA across all regions. In addition, JJA (DJF, MAM, JJA, SON, annual) across most (all) regions showed the greatest number of nonsignificant (significant) positive and negative abrupt changes.

For the long-term changes, the first three decades (1970–1979, 1980–1989, and 1990–1999) across seasons exhibited (Fig. 7) strong negative anomalies across the whole country in range of −0.01 to −1.0 °C/decade), with the exception of positive anomalies in DJF during 1990–1999 (0.01–0.40 °C/decade). During the last decades of 2000–2009 and 2010–2014), strong positive changes (0.01–1.0 °C/decade) in temperature were exhibited across most of Pakistan. However, negative changes were also observed over patches in the northwest (−0.02 to −0.04 °C/decade) during the 2010–2014 DJF season.

In conclusion, this work establishes baseline information to aid in devising climate change mitigation and adaptation strategies at the subregional and national levels in Pakistan. It is well proven that interannual temperature anomalies are linked to interannual variations of quasi-periodic changes in the atmospheric physical process such as ENSO, Indian Ocean Dipole, NAO, and AO. Therefore, further studies are required to analyse the impact of changes in atmospheric processes on surface temperature anomalies to understand the role of such mechanisms and the development of strong warming adaptive mechanisms.

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Author Contributions Conceptualization: RK and GT; Methodology: RK, GT, and BA; Software: RK, MAAA, HN and HB; Data Curation and Validation: RK, GT and HB; Formal Analysis: RK, BA and HB; Writing—Original Draft Preparation: RK, GT and BA; Review And Editing: RK, GT, MAAA, HN; Supervision GT.

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Availability of Data and Materials

The Climate Research Unit (CRU) dataset used in this study is freely available at the repository [https://crudata.uea.ac.uk/cru/data/hrg/] of the School of Environmental Sciences at the University of East Anglia.

Declarations

Conflict of Interest The authors have no relevant financial or non-financial interests to disclose. All authors solemnly declare no conflict of interest involved for this study.

Ethical Approval This work is carried out following the regulations defined guidelines by Nanjing University of Information Science and Technology for ethical standards in data collection, curation and presentation.

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