Half a Century of Warming in Punjab, Pakistan: Statistical Evidence from 1970–2019

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Regional temperature gradients affect how climate change is defined and assessed from varying perspectives. In this research, temperature trends in the Province of Punjab from 1970 to 2019 were examined. To assess the changes in temperature, the monthly means of temperature (Tmean), maximum temperature (Tmax), and minimum temperature (Tmin) were analyzed using Sen's slope estimator method. Several empirical techniques are applied to assess whether the trends are indeed significant, either positively or negatively, and to what extent diversity exists among different weather stations. Also considered are the expected values in the determination of a comprehensive account of temperature fluctuation and variation. The analysis indicates a significant increase in the mean temperature (Tmean) across Punjab, with a sharper increase from Northern Punjab to Southern Punjab. While maximum temperature (Tmax) shows a steep increase in southern and western regions, minimum temperature (Tmin) shows a predominantly increasing trend in central Punjab. Results show a statistically significant warming trend, with mean temperature increasing at 0.04°C per year. Southern and Western Punjab experienced higher rates of warming compared to Northern regions. Maximum temperatures increased more sharply in the south, while minimum temperatures rose more prominently in central Punjab, indicating a declining diurnal temperature range. These findings highlight regional climate disparities and underscore the need for targeted adaptation strategies. These findings are going to be useful to those making national policy who are trying to formulate strategies for climate change mitigation and adaptation.

Keywords: Climate Adaptation, Long-Term Temperature Trends, Change Rate, Seasonal and Regional Temperature

Introduction:

Climate change is most commonly assessed through the systematic analysis of long-term and spatial temperature trends. An evaluation of temperature records spanning the past century reveals a persistent and statistically significant increase in global mean temperatures, thereby providing robust empirical evidence in support of contemporary climate change assertions. If these temperature increases remain unmitigated, they are likely to result in irreversible degradation of global ecosystems. According to [1], the direct impacts of climate change encompass alterations in rainfall regimes, water availability, agricultural productivity, and human health, affecting both natural and socio-economic systems. In contrast, indirect impacts manifest within institutional, political, economic, demographic, and technological domains. Consequently, the comprehensive analysis of long-term temperature records constitutes a critical prerequisite for accurately assessing and projecting the impacts of climate change, as consistently emphasized in the literature [2][3][4][5][6][7].

Pakistan is among the countries most severely affected by climate change and faces compounded challenges arising from diminishing natural resources, sensitive physiographic conditions, and predominantly arid to semi-arid climatic regimes. Over the past several decades, the country has experienced a series of severe and catastrophic extreme climatic events, including floods, droughts, storms, and landslides, which have resulted in substantial human casualties and considerable economic losses. The intensity, duration, and frequency of these climate-induced events are projected to intensify further and occur more frequently in the future [8]. Recent assessments indicate that Pakistan ranks 12th on the global climate vulnerability index and incurs annual economic losses estimated at approximately USD 5 billion [9]. Agriculture constitutes the primary livelihood for a substantial proportion of Pakistan's population, thereby amplifying the sector's exposure and sensitivity to climatic variability [10][11][12].

The analysis of temperature trends is particularly critical, as even marginal increases can exert profound effects on human well-being and environmental stability at regional and global scales. Projections suggest that northeastern regions of Pakistan and India are likely to experience the most pronounced and extreme increases in temperature. In contrast, rainfall patterns have thus far exhibited considerable spatial and temporal variability, with summer rainfall contributing prominently to the observed variability framework. According to [13], dry and semi-arid regions globally tend to experience amplified temperature fluctuations. Notably, rising temperature trends have been observed across the northern regions of Pakistan, India, and western China. The International Fund for Agricultural Development [14] has reported a more accelerated warming trend in these northern regions, a finding that has been consistently corroborated by numerous studies conducted worldwide [15][7][1].

A substantial body of contemporary scientific literature has focused on assessing temperature trends and variability across Pakistan [16][17][18][10][19][20][21][22][11][9][23][24]. According to [25], the national average temperature of Pakistan has increased by approximately 0.6 °C over the last century. Such rapid warming trends are further underscored by findings reported in [9], which reveal that increases in maximum temperatures have been significantly greater than those observed in minimum temperatures.

Despite these advances, a critical gap remains in the literature concerning detailed assessments of recent temperature trends and variability at the provincial and sub-regional scales. This study seeks to address this gap by providing a comprehensive evaluation of regional temperature variations within Punjab province through its division into four distinct regions, each characterized by unique agricultural production systems. By doing so, the study delivers region-specific climatic insights that facilitate a clearer differentiation of intra-provincial climate regimes within Punjab. The findings of this research are intended to serve as an empirical foundation for the formulation of targeted and regionally responsive agricultural policies in the context of climate change.

Study Area:

Punjab province is situated in South Asia between latitudes 27°–34° N and longitudes 69°–75° E. Administratively, the province comprises 37 districts. Following the classification proposed in [26], Punjab can be regionally subdivided into four zones: Northern, Central, Southern, and Western Punjab. This regional delineation is based on the interaction of physiographic features, canal-based irrigation networks, and prevailing cropping patterns.

The spatial distribution of meteorological observatories across Punjab, which constitute a major source of long-term climatic data operated by the Pakistan Meteorological Department (PMD), is illustrated in Figure 1. The figure also presents the digital elevation model of the province, highlighting mountainous terrain along the northwestern and western margins, while the remaining areas are dominated by extensive alluvial plains. According to [28], Punjab province predominantly falls within a dry climatic zone. Nevertheless, pronounced climatic heterogeneity exists across the province: Northern Punjab exhibits humid to sub-humid conditions, Central Punjab reflects characteristics of a tropical climate, and Southern Punjab displays climatic features more closely aligned with coastal-type regimes.

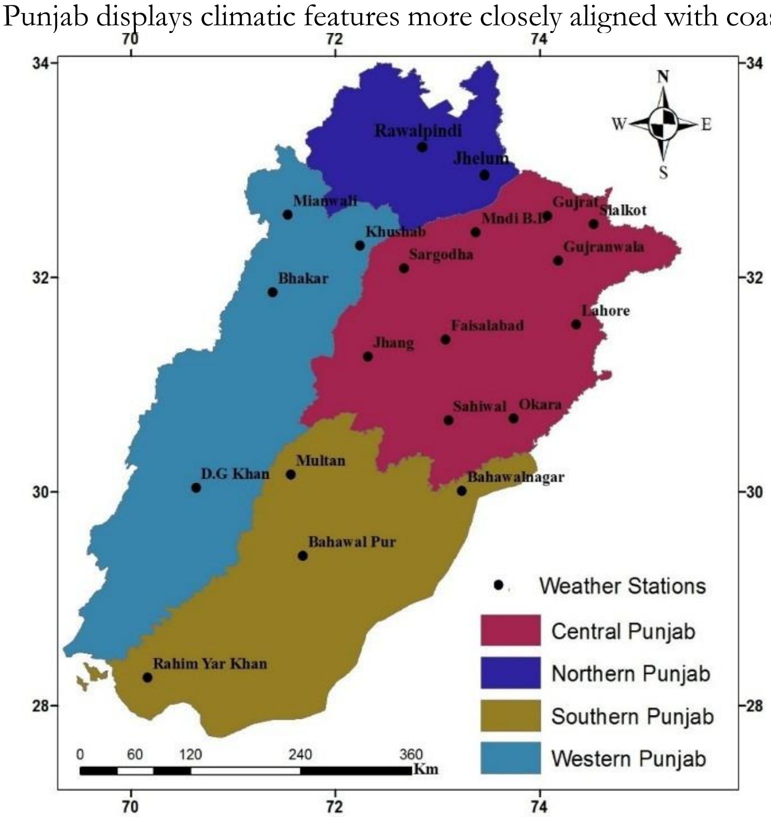

Figure 1. Location map of investigating meteorological stations over the Punjab region, Pakistan.

Table 1 summarizes the geographical and climatic characteristics of the identified regions. The Northern region is predominantly rain-fed, whereas the Central region receives substantially higher annual precipitation than the Southern region. The Southern region is comparatively arid, rendering irrigation infrastructure essential for sustaining agricultural productivity. Indeed, the southern plains of Punjab rely extensively on artificial irrigation systems to maintain crop yields. Maximum temperatures typically peak during the summer months across the plains of Pakistan, as reported by [9]. Moreover, several studies, including [27], have documented a gradual increase in winter temperatures in both Central and Southern Punjab.

Materials and Methods:

Spatio-temporal trends in long-term variability of maximum (Tmax), minimum (Tmin), and mean (Tmean) temperatures were analyzed over 50 years (1970–2019). Data were collected from 20 meteorological stations across Punjab (Pak. Met. Dep) as given in Figure 1.

$$Yi = xi - (\beta \times i) \quad (1)$$

Table 1. Characteristics of classified regions of Punjab, Pakistan

Features	Northern	Central	Western	Southern
Latitude	33.10° - 34.09° N	30.12° - 33.09° N	28.52° - 33.49° N	27.89° - 30.05° N
Longitude	71.99° - 76.35° E	71.79° - 75.45° E	69.52° - 72.69° E	69.92° - 74.01° E
Climate types	Subtropical	Humid subtropical	Subtropical semiarid	Arid
Annual Tmax (°C)	31.45	30.75	31.77	32.70
Annual Tmin (°C)	19.44	18.89	16,90	18.58
Annual Tmean (°C)	26.67	24.87	24.57	25.68
Summer *T*max (°C)	35.34	36.61	38.04	39.88
Summer *T*min (°C)	25.74	26.69	24.32	27.79
Summer Tmean (°C)	30.89	31.99	31.80	33.44
Winter *T*max (°C)	19.70	21.90	22.40	22.50
Winter *T*min (°C)	9.43	8.380	10.40	11.40
Winter Tmean (°C)	15.23	14.63	15.93	16.23

The Mann–Kendall (MK) test was employed to detect significant trends in the temperature data. This non-parametric method is widely used for climatological and hydrological time series due to its robustness against assumptions of data distribution and independence. Removal of serial correlation on longitudinal spots was considered before the applicability of the MK.

$$Y'i = Yi - rY1{-}i + (\beta \times i) \quad (2)$$

Mann–Kendall statistic [29] was utilized in this research work to evaluate the randomness against our resultant trends. The MK test does not require any assumptions about the distribution of irregularly spaced data over time.

The Mann–Kendall statistic Zmk reads:𝑄𝑄 (𝑁+1)

if N was odd

$$F(S) = \begin{cases} \frac{S-1}{2}, & S > 0, \\ 0, & S = 0, \\ \frac{S+1}{2} Q_S, & S < 0. \end{cases}$$

For the two-decade period, the student's t-test is utilized to determine the statistical significance of the mean values over a given time. The confidence level for both tests

The MK test statistic *S* reads:

Was set at 90%. We use a t-test as per the following

$$t = \bar{X}_1 - \bar{X}_2 \quad \text{eq (1)}$$

$$\sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sg}(x_{jj} - x_k) \quad \text{eq (2)}$$

In this equation, *n* = number of years, Xj and Xk = sample values, where j indicates the annual time instants and k represent the seasonal time instants consecutively. The functional sgn (x -x) corresponds

$$S\left(\frac{1}{n_1} + \frac{1}{n_2}\right)$$

X¯R1 and X¯R2\bar{X}_{R2}X¯R2 = mean values; n1n_1n1 and n2n_2n2 = number of observations.

j k numbers, s1 and s2 = standard deviations, where

to the values 1, 0, or -1 as per sign difference (xj-xk), it is the functional indicator where j>k:

$1\ if\ x_{jj} - x_k > 0$

Subscripts 1 and 2 show the time duration (1970-1998) and (1999-2019). Sp = pooled standard deviation that can be expressed with the following equation:

$$\mathrm{sgn}(x_{jj} - x_k) = \begin{cases} 0, & x_{jj} - x_k = 0, \\ -1, & x_{jj} - x_k < 0. \end{cases}$$

$$p = \frac{(n_1 + 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}.$$

Zmk values are used to represent the general trends of variables. In 1968, Sen developed a non-parametric technique to estimate the trend slope in the data that T- statistic can be measured by the following equation if the variances of the two-time durations are not similar, and have linear trends according to the time series. Sen's slope method is used to detect the rate of change in the temperature. The equation shows a slope of two kinds of observations in given time instants *k* and *j*:

$$t = \frac{X_1 - X_2}{\frac{1}{n_1} + \frac{1}{n_2}}$$

Assessment of Long-Term Temperature Trends in Punjab, Pakistan Using Mann-Kendall Test and Sen's Slope Estimator

```
# Pseudo-code for analyzing long-term temperature trends in Punjab
# Import necessary libraries
import pandas as pd
import numpy as np
from pymannkendall import original_test  # For Mann-Kendall trend test
# Step 1: Load temperature data from meteorological stations
# Assume 'temperature_data.csv' has columns: 'Station', 'Year', 'Month', 'Tmax', 'Tmin',
'Tmean'
data = pd.read_csv('temperature_data.csv')
# Step 2: Preprocess data
# Calculate annual and seasonal averages for Tmax, Tmin, Tmean
def calculate_annual_average(df, temp_type):
    return df.groupby(['Station', 'Year'])[temp_type].mean().reset_index()
annual_Tmax = calculate_annual_average(data, 'Tmax')
annual_Tmin = calculate_annual_average(data, 'Tmin')
annual_Tmean = calculate_annual_average(data, 'Tmean')
# Step 3: Mann-Kendall Trend Test for each station
def compute_MK_test(df, temp_type):
    results = {}
    for station in df['Station'].unique():
        station_data = df[df['Station'] == station][temp_type].values
        mk_result = original_test(station_data)  # Returns trend, h, p-value, slope, intercept
        results[station] = mk_result
    return results
mk_Tmax = compute_MK_test(annual_Tmax, 'Tmax')
mk_Tmin = compute_MK_test(annual_Tmin, 'Tmin')
mk_Tmean = compute_MK_test(annual_Tmean, 'Tmean')
```

```
# Step 4: Sen's slope estimation (included in MK test result)
# The slope indicates the rate of temperature change per year
# Step 5: Output results
# Save trend analysis and slope values for reporting
def save_results(results, filename):
    df_results = pd.DataFrame.from_dict(results, orient='index')
    df_results.to_csv(filename)
save_results(mk_Tmax, 'MK_results_Tmax.csv')
save_results(mk_Tmin, 'MK_results_Tmin.csv')
save_results(mk_Tmean, 'MK_results_Tmean.csv')
# Step 6: Visualization (optional)
# Plot trends using matplotlib or seaborn
```

To maintain clarity, the Results section now presents findings only, while the Discussion provides interpretation within the regional climatic context.

$$Q_i = \frac{x_{jj} - x_k}{j - k} \quad \text{if } j > k.$$

Assessment of annual and seasonal variability of Temperature:

Sen's estimator is the median Qmed of the N pairs of Q_i. In the procedure, N values of Q_i are ranked from smallest to largest, and Sen's estimator reads:

$Sen'sestimator =$

The Northern region of Punjab has more rainfall in the summer monsoon season, and its variability is less found as compared to the Southern and Western Punjab (Fig. 2a). The Central Region of Punjab is attributed to the zone of high rainfall (Fig. 2b).

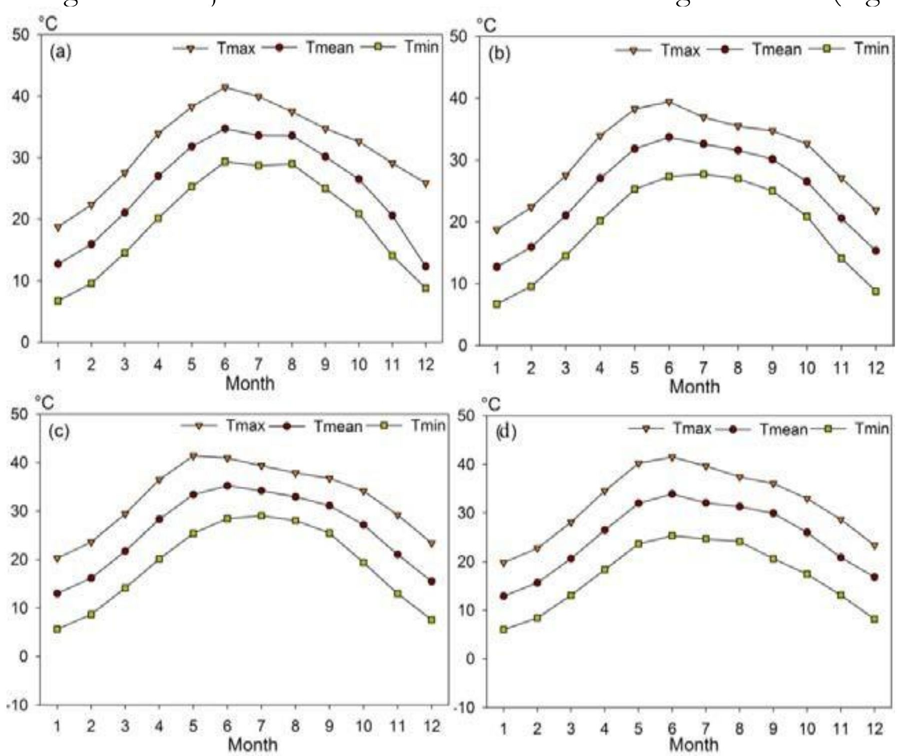

Figure 2. Temporal patterns of temperature over the Punjab regions (a) Northern Punjab, (b) Central Punjab, (c) Western Punjab, (d) Southern Punjab.

Comparatively, the Southern zone is a little drier than the Western region:

Punjab contains extensive arid zones, with more than 65% of its population residing in rural areas. The maximum temperature (Table 3) in the Gujrat district exhibited an increasing trend at a rate of 0.27 °C per year. The results indicate that Gujrat in Central Punjab and Khushab in Western Punjab are the meteorological stations demonstrating statistically significant increasing temperature trends.

The graphical illustrations reveal that the population of Punjab remains heavily dependent on agriculture. During the months of June and July, maximum temperatures (Tmax) typically reach extremely high levels, a pattern clearly illustrated in Figures 2c and 2d. These findings further emphasize the dominance of extensive plain regions, particularly across Western Punjab.

Figures 3a (annual temperature trends), 3b (Kharif season trends), and 3c (Rabi season trends) delineate the spatial distribution of regions within Punjab province exhibiting statistically significant temperature trends at the 0.05 significance level, evaluated on both annual and seasonal timescales.

Based on the observed trends, Tmax has increased at an average rate of approximately 0.040 °C per year, whereas Tmin has risen at a comparatively higher rate of about 0.050 °C per year, with the Central region of Punjab experiencing the most pronounced warming. Consistent with the analysis of variance presented in Table 2, the spatial assessment demonstrates that temperature trends vary considerably across regions, often occurring in opposing directions and with differing magnitudes.

A detailed regional analysis of Tmax, Tmin, and Tmean was conducted for the northern, central, western, and southern regions of Punjab. In Northern Punjab, the districts of Jhelum and Rawalpindi exhibited relatively modest increases in Tmax, with an average rise of 0.19 °C per year. In contrast, the increase in Tmin was substantially more pronounced in these areas. Specifically, Jhelum recorded an increase of 0.45 °C per year in Tmin, while Rawalpindi exhibited an increase of 0.33 °C per year. The associated significance values for these trends were 0.62 and 0.396, respectively.

Table 2. F-values of mean, maximum, and minimum temperature in t and f test oC (1979-2019).

Sr. no.	Punjab		Tmean		Tmax		Tmin	
	Region	Stations	F-value	Sig	F-value	Sig	F-value	Sig.
1	Northern	Jhelum	21.66	0.00	3.635	0.038	71.579	0.012
2		Rawalpindi	4.946	0.02	1.492	0.229	87.883	0.001
3	Southern	Multan	0.943	0.33	1.992	0.166	7.95	0.008
4		Bahawalnagar	10.465	0.00	3.53	0.069	15.382	0.001
5		R.Y khan	6.009	0.01	20.642	0	0.3991	0.532
6		Bahawalpur	2.548	0.11	0.381	0.541	4.387	0.043
7	Central	Gujrat	0.391	0.00	2.943	0.048	0.880	0.000
8		Sialkot	12.082	0.00	2.065	0.165	35.342	0.003
9		Gujranwala	5.636	0.00	8.346	0.006	1.019	0.319
10		M.Bahuddin	20.66	0.00	4.635	0.038	21.579	0.002
11		Sargodha	5.946	0.024	1.492	0.229	87.883	0.001
12		Lahore	4.96	0.001	1.382	0.247	24.99	0.002
13		Faisalabad	13.454	0.00	0.545	0.465	52.278	0.001
14		Sahiwal	40.707	0.002	50.268	0.005	20.58	0.003
15		Okara	1.949	0.171	0.31	0.581	1.98	0.167
16		Jhang	14.186	0.001	7.299	0.01	9.159	0.004
17	Western	Mianwali	0.085	0.002	8.643	0.004	17.313	0.035
18		Khushab	67.79	0.00	83.153	0.002	15.53	0.001
19		D.G khan	50.186	0.00	13.782	0.001	50.18	0.002
20		Bhakkar	4.226	0.047	0.305	0.584	11.189	0.003

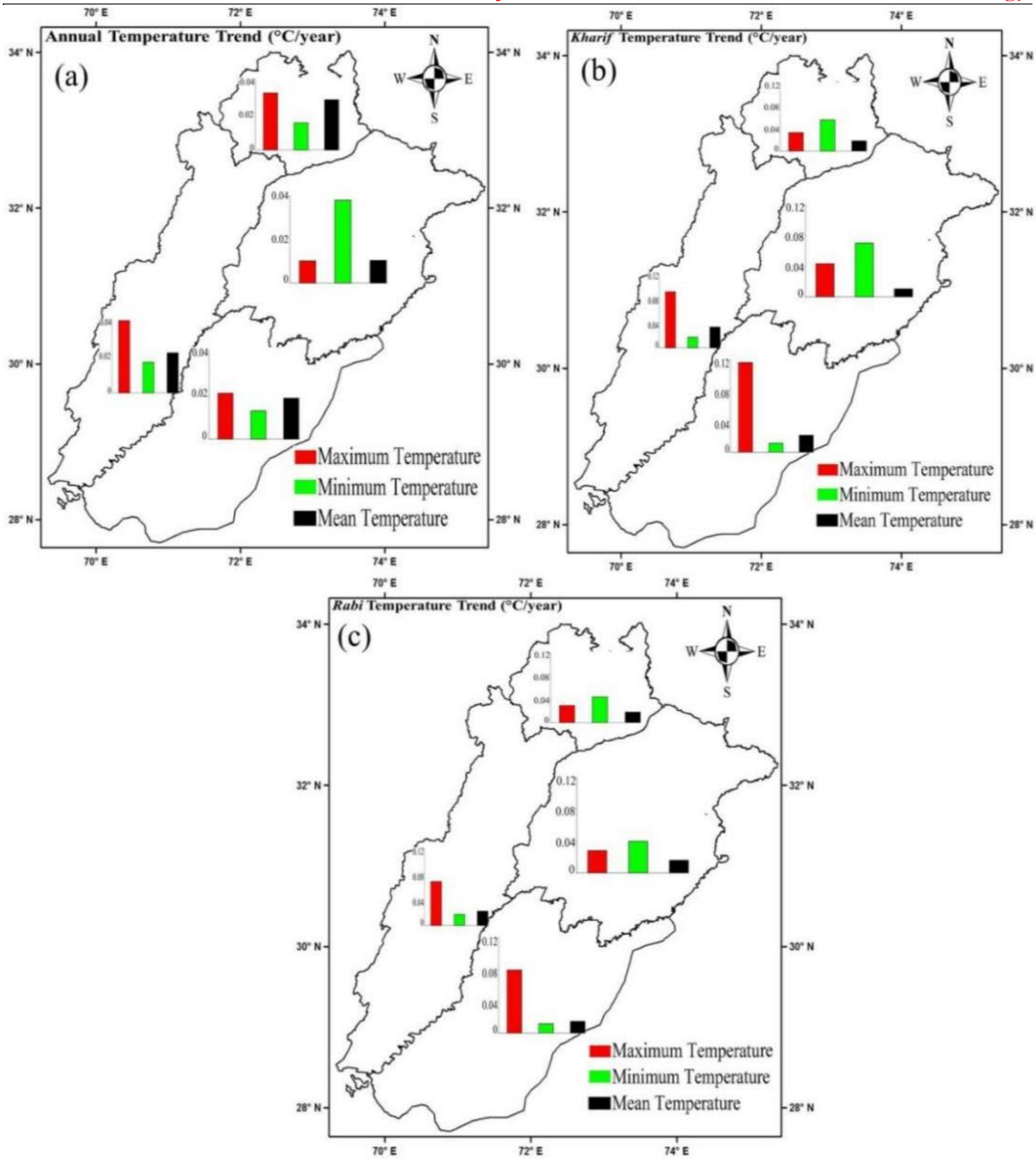

Figure 3. Trends of temperature over the Punjab regions of Pakistan (a) Annual temperature (°C) (b) Kharif temperature (°C) (c) Rabi temperature (°C) from 1979-2019.

A consistent and smooth increasing trend in minimum temperature was observed from Southern Punjab toward Central Punjab, with the most pronounced increase recorded in Lahore (Central Punjab), where the coefficient of determination (R^2) reached 0.396 (Table 5). Elevated minimum temperatures were also recorded in Dera Ghazi Khan (D.G. Khan) in Southern Punjab. Furthermore, the results indicate that the increase in mean temperature was greater in Central Punjab, particularly in Sahiwal, compared to Western Punjab, represented by Khushab (Table 4). Analysis of maximum temperature trends revealed a positive and statistically significant upward pattern across all districts, with the exception of Lahore in Central Punjab and Bahawalpur in Western Punjab.

A statistically significant rise in minimum temperature over the study period was observed in Gujrat, Sargodha, and Faisalabad, with corresponding F-values of 0.88, 87.883, and 52.278 and associated p-values of 0.000, 0.001, and 0.001, respectively (Table 2). Among these divisions, Gujrat also exhibited a comparatively smaller yet statistically significant increase in maximum temperature, with a p-value of 0.048. Overall, the Central region demonstrated a more rapid rate of increase in minimum temperature relative to other regions. Notably, minimum temperatures in Central Punjab were observed to be higher than maximum temperature increases, a finding of particular concern given that this region represents the most densely populated area of Punjab, Pakistan.

Table 3. Shows the Change rate and trend Sig of temperature oC (1979-2019).

Sr. no.	Region	Station	Tmean		Tmax		Tmin	
			Change rate	Sig.	Change rate	Sig.	Change rate	Sig.
1	Northern	Jhelum	0.04	0.36	(0.01)	(0.19)	0.06	0.45
2		Rawalpindi	0.03	0.33	(0.01)	(0.19)	0.05	0.33
3	Southern	Multan	0.01	0.16	(0.01)	(0.22)	0.02	0.42
4		Bahawalnagar	0.03	0.46	0.02	0.29	0.03	0.54
5		R.Y khan	0.02	0.37	0.05	0.59	(0.01)	(0.10)
6		Bahawalpur	0.03	0.25	0.01	0.10	0.04	0.32
7	Central	Gujrat	0.00	0.09	0.02	0.27	(0.01)	(0.15)
8		Sialkot	0.02	0.49	0.01	0.16	0.04	0.69
9		Gujranwala	(0.02)	(0.36)	(0.03)	(0.42)	(0.01)	(0.16)
10		M.Bahuddin	(0.08)	(0.59)	(0.02)	(0.33)	(0.14)	(0.60)
11		Sargodha	0.07	0.36	(0.01)	(0.19)	0.06	0.85
12		Lahore	0.02	0.34	(0.01)	(0.19)	0.05	0.63
13		Faisalabad	0.02	0.51	0.01	0.12	0.04	0.76
14		Sahiwal	0.06	0.72	0.06	0.75	0.06	0.59
15		Okara	(0.01)	(0.22)	(0.00)	(0.09)	(0.01)	(0.22)
16		Jhang	(0.06)	(0.52)	0.03	0.40	(0.06)	(0.44)
17	Western	Mianwali	(0.02)	(0.05)	(0.02)	(0.43)	0.03	0.56
18		Khushab	0.07	0.80	0.19	0.83	(0.06)	(0.54)
19		D.G khan	0.05	0.76	0.03	0.52	0.06	0.76
20		Bhakkar	0.02	0.32	(0.01)	(0.09)	0.03	0.48

The detailed analysis revealed a statistically significant upward trend in maximum temperatures across the Gujranwala, Sargodha, and Sahiwal divisions. In Central Punjab, rapid and extensive urbanization—including the expansion of housing schemes, transportation infrastructure, industrial zones, and major road networks—has substantially contributed to rising minimum temperatures. Furthermore, the increased use of motor vehicles has intensified the combustion of fossil fuels and petroleum products, leading to elevated emissions of carbon-containing gases into the atmosphere. These processes have preferentially enhanced minimum temperatures relative to maximum temperatures, resulting in Tmin emerging as the more significant warming indicator in this region.

The most pronounced warming trend was observed in Southern Punjab, with an annual temperature increase of 0.024 °C per year. The year 2016, identified as the warmest year on record, exhibited a positive temperature anomaly of 0.8 °C. Maximum temperatures during this period also demonstrated a marked upward trajectory. In Western Punjab, both maximum and minimum temperatures displayed increasing trends. Specifically, the districts of Mianwali, Khushab, and Dera Ghazi Khan (D.G. Khan) recorded statistically significant increases in minimum temperature, with corresponding F-values of 17.313, 15.53, and 50.18 and significance values of 0.035, 0.001, and 0.002, respectively. These divisions also exhibited statistically significant increases in maximum temperature (Table 2). Overall, Western Punjab experienced a warming rate of 0.019 °C per year, with 2014 identified as the warmest year, characterized by a positive temperature anomaly of 1.23 °C.

Table 4. Observed and predicted R2 value of the mean temperature oC (1979-2019).

Sr. no.	Region	Station	R	R2	Adjusted R2	Predicted R2
1	***Northern***	Jhelum	0.133	0.115	0.042	0.23
2		Rawalpindi	0.521	0.262	0.222	0.02
3	***Southern***	Multan	0.156	0.024	-0.001	0.025
4		Bahawalnagar	0.465	0.216	0.195	0.021
5		R.Y khan	0.37	0.137	0.114	0.023
6		Bahawalpur	0.251	0.063	0.038	0.025
7	***Central***	Gujrat	0.091	0.008	-0.018	0.026
8		Sialkot	0.491	0.241	0.221	0.02
9		Gujranwala	0.359	0.129	0.106	0.023
10		M.Bahuddin	0.593	0.352	0.335	0.017
11		Sargodha	0.355	0.126	0.103	0.023
12		Lahore	0.34	0.115	0.092	0.023
13		Faisalabad	0.511	0.262	0.242	0.02
14		Sahiwal	0.719	0.517	0.504	0.013
15		Okara	0.221	0.049	0.024	0.025
16		Jhang	0.521	0.272	0.253	0.019
17	***Western***	Mianwali	0.047	0.002	-0.024	0.026
18		Khushab	0.8	0.641	0.631	0.01
19		D.G khan	0.756	0.572	0.561	0.011
20		Bhakkar	0.316	0.1	0.076	0.024

Table 5. Observed and predicted R2 value of the minimum temperature oC (1979-2019).

Sr. no	Region	Stations	R	R2	Adjusted R2	Predicted R2
1	***Northern***	Jhelum	0.749	0.62	0.713	0.013
2		Rawalpindi	0.429	0.396	0.38	0.011
3	***Southern***	Multan	0.416	0.173	0.151	-0.002
4		Bahawalnagar	0.573	0.268	0.27	0.026
5		R.Y khan	0.102	0.01	-0.016	0.018
6		Bahawalpur	0.322	0.103	0.08	0.021
7	***Central***	Gujrat	0.15	0.023	-0.003	0.022
8		Sialkot	0.694	0.481	0.459	0.024
9		Gujranwala	0.162	0.026	0.002	0.017
10		M.Bahuddin	0.602	0.362	0.345	0.007
11		Sargodha	0.849	0.72	0.713	0.016
12		Lahore	0.629	0.396	0.38	0.011
13		Faisalabad	0.761	0.579	0.568	0.023
14		Sahiwal	0.593	0.351	0.334	0.025
15		Okara	0.223	0.05	0.025	0.011
16		Jhang	0.441	0.194	0.173	0.022
17	***Western***	Mianwali	0.559	0.313	0.295	0.026
18		Khushab	0.539	0.29	0.272	0.017
19		D.G khan	0.756	0.572	0.561	0.02
20		Bhakkar	0.447	0.227	0.207	0.023

An increasing temperature trend of 0.0020 °C and 0.039 °C per year was observed in Southern Punjab. The maximum temperature in the Multan division exhibited a statistically significant upward trend. Similarly, within Southern Punjab, Bahawalnagar demonstrated the most pronounced increase in minimum temperature, with an F-value of 15.382 and a significance value of 0.001. In contrast, the same division showed an insignificant increase in maximum temperature. Western Punjab exhibited increasing temperature trends of 0.0020 °C and 0.039 °C per year.

On average, the increasing trend in minimum temperature across Southern and Western Punjab was observed to range between 0.013 and 0.018 °C per year. Seasonal analysis for both the Kharif and Rabi periods revealed temperature trends consistent with those observed for annual temperatures (Figures 2b and 2c). Spatial analysis further indicates that the trend direction of maximum temperature (Table 3) shows a significant increase in the Khushab district, with a rate of 0.87 °C per year. A statistically significant coefficient of determination (R^2) of 0.352 was recorded for maximum temperature in the Khushab district.

The assessment of regional variations in maximum and minimum temperatures indicates a rising trend in minimum temperature alongside a declining trend in maximum temperature for future projections. The results reveal a concerning upward progression in minimum temperatures from Southern to Central Punjab, followed by a decreasing trend from Central to Northern Punjab. Furthermore, the findings highlight that the Central Punjab divisions of Sargodha and Faisalabad are experiencing the most substantial increases in minimum temperature.

Table 6. Observed and predicted R2 value of the maximum temperature oC (1979-2019).

Sr. no	Region	Stations	R	R2	Adjusted R2	Predicted R2
1	***Northern***	Jhelum	0.177	0.045	0.01	0.025
2		Rawalpindi	0.129	0.054	0.012	0.026
3	***Southern***	Multan	0.223	0.161	0.025	0.136
4		Bahawalnagar	0.291	0.05	0.06	-0.01
5		R.Y khan	0.593	0.084	0.335	-0.251
6		Bahawalpur	0.1	0.103	-0.016	0.119
7	***Central***	Gujrat	0.268	0.072	0.048	0.024
8		Sialkot	0.224	0.05	0.025	0.025
9		Gujranwala	0.424	0.18	0.159	0.021
10		M.Bahuddin	0.33	0.109	0.085	0.024
11		Sargodha	0.194	0.038	0.123	-0.085
12		Lahore	0.187	0.035	0.01	0.025
13		Faisalabad	0.119	0.014	-0.012	0.026
14		Sahiwal	0.755	0.686	0.558	0.128
15		Okara	0.09	0.564	-0.018	0.582
16		Jhang	0.401	0.101	0.139	-0.038
17	***Western***	Mianwali	0.43	0.185	0.164	0.021
18		Khushab	0.832	0.352	0.678	-0.326
19		D.G khan	0.514	0.008	0.247	-0.239
20		Bhakkar	0.089	0.226	-0.18	0.406

The predicted R^2 values, representing future trends in mean, maximum, and minimum temperatures, indicate that both maximum and minimum temperatures are projected to increase in Northern Punjab. In contrast, Southern Punjab exhibits a distinct pattern, wherein Rahim Yar Khan and Bahawalnagar are projected to experience declining trends in maximum temperature, reflected by predicted R^2 values of −0.251 and −0.01, respectively. Nevertheless, both Rahim Yar Khan and Bahawalnagar demonstrate increasing trends in minimum temperature, with predicted R^2 values of 0.018 and 0.026, respectively.

In Central Punjab, a negative trend in maximum temperature is projected for the Sargodha and Jhang divisions, with predicted R^2 values of −0.085 and −0.038, respectively.

Conversely, both divisions exhibit positive increasing trends in minimum temperature, with predicted R^2 values of 0.016 and 0.022, respectively. Similarly, in Western Punjab, the districts of Khushab and Dera Ghazi Khan (D.G. Khan) are projected to experience decreases in maximum temperature, as indicated by predicted R^2 values of −0.326 and −0.239, respectively. In contrast, both districts are expected to show slight but consistent increases in minimum temperature, with predicted R^2 values of 0.017 and 0.020, respectively.

Overall, these projections suggest that three of the four regions—Central, Western, and Southern Punjab—are undergoing notable temperature changes. In Southern Punjab, the increasing trend in minimum temperature may adversely affect Rabi crops, as accelerated crop maturity can result in reduced grain size and lower yields. Moreover, the persistent rise in minimum temperatures is likely to exacerbate land degradation processes in this region, contributing to broader environmental intensification.

Central Punjab, despite its predominantly flat terrain, exhibits rising minimum temperatures driven by high population density and rapid urbanization. The region continues to attract population inflows due to employment opportunities and improved access to health and educational facilities. Consequently, extensive forested and agricultural lands are increasingly being converted into housing developments, industrial zones, and transportation infrastructure. Furthermore, maximum temperatures in Southern and Western Punjab are observed to be higher than those in Central and Northern Punjab.

Conclusion:

The present study investigates the spatial and temporal variability of temperature across Punjab Province, Pakistan, over the period 1979–2019. The Mann–Kendall trend test and Sen's slope estimator were employed to evaluate spatiotemporal trends in temperature. The results reveal statistically significant positive trends in minimum and mean annual temperatures across Northern and Central Punjab. In contrast, maximum temperature trends exhibit both insignificant positive and negative variations across different regions.

Notably, the rate of increase in minimum temperature exceeds that of maximum temperature, leading to a reduction in the diurnal temperature range (DTR), particularly in Southern Punjab, alongside increasing maximum temperature trends in Western Punjab. These findings highlight the growing thermal stress across the province. The outcomes of this study provide valuable insights for policymakers, particularly in updating crop sowing and harvesting calendars, which are central to Punjab's agricultural economy. Additionally, regions experiencing pronounced fluctuations in both maximum and minimum temperatures are likely to face escalating water demands under future warming scenarios, coupled with reduced water availability due to increasingly erratic rainfall patterns.

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