Journal of Himalayan Earth Sciences Volume , No., 2026 pp. 1-20

Evolving Rainfall Regimes in Pakistan: Insights from a Dual-Period Spatiotemporal Analysis

Abdul Jameel Khan[1], Kamran Khan[2], Atia Elahi[3*], and Saqib-Ur-Rehman[1]

[1]*Department of Mathematical Sciences, University of Karachi, Pakistan*
[2]*Department of Computer Sciences, Iqra University, Karachi, Pakistan*
[3]*Department of Management Sciences, Iqra University, Karachi, Pakistan*
**Corresponding Author: atia.elahi@iqra.edu.pk*

Submitted Date:02/01/2026 Acceptance Date: 29/04/2026 Publication Date:---------

Abstract

Climate change is closely linked with rate of precipitation and proper monitoring and assessment this phenomenon is important for sustainable development. This study explores the Pattitt and Modified Mann-Kendall (MMK) trend test to observe the changes in median and trends analysis in precipitation in the dual-period: 1951-2019 and 1981-2019 as model. The results revealed a significant shift in median precipitation across Pakistan for pre-1981. From 1951 to 1980, changes were concentrated in the northern regions of Jammu and Kashmir (JK) and Khyber Pakhtunkhwa (KP), alongside the borders of Balochistan (BL) and Punjab (PJ). After 1981, it broadened, affecting the northern areas of Gilgit Baltistan (GB), Federally administered tribal areas (FATA), and KP, beside the southern coastline of BL and Sindh. The shifts indicate a southward migration of precipitation variability, particularly post-1981. The results of the MMK test showed across seasons, significant precipitation variations occurred, with a minor long-term surge, except in summer and autumn, which showed a more substantial rise. Especially July and August were major contributors to summer precipitation. Short-term intervals consistently experienced over half of the long-term precipitation, especially with more rapid declines in cool seasons. In specific regions like GB and BL, Winter precipitation declined significantly in the short term, while northern sectors of PJ exhibited amplified long-term precipitation. Cool-season precipitation increases, especially in some areas of PJ, Sindh, and KP. Springtime precipitation increased in various regions during the short term. Summer precipitation patterns were driven by monsoon and snowmelt, causing flash floods. PJ showed deviating trends in precipitation, with some regions experiencing intensified rainfall over the long-term.

Keywords: Precipitation; Long-term change; Short-term change; Mann-Kendell trend; Pattitt's test; climate variability

1. Introduction

Pakistan located around 60° to 80 longitude and 22 to 38 latitudes, has a significant role in South Asia, encompassing a region of 803,943 square kilometers (Ali et al., 2022). The topography of Pakistan exhibits remarkable diversity, with the northern areas featuring towering peaks in the Himalayas and Karakoram ranges. At the same time, the central areas encompass low-lying plains in PJ and BL provinces, as well as coastal zones in southern Sindh (Figure 4). The Northern ranges are highly subtle in terms of climate variation (Bhatta et al., 2020; Kamal et al., 2018) and are of global importance (Xu et al., 2014). This diversity in the altitude not only impacts the country's climate and vegetation (Xu et al., 2014) but also plays a significant role in its culture, economy, history, and outdoor recreational activities (tourism) (Arshad et al., 2018). The upper Indus basin, which serves as the primary freshwater source for the country, is bounded by the northern mountain chains of the Himalayas and the Karakoram (Iqbal et al., 2019). The GB region lies in the

Himalayas, the Karakoram, and the Hindu-Kush chains of the country (Figure 4). The annual precipitation in this region bears no significant change (Iqbal et al., 2019).

Waseem et al. (2020) conducted a study in the southwestern district of the country, covering the Baluchistan and southern Sindh provinces, including Karachi. This research involved 13 meteorological stations and covered 43.6% of the country's area. Among many findings, the study shows that the region's precipitation pattern is erratic, with abrupt changes occurring over short distances. For instance, in the Soan River Basin of the sub-Himalayan Pothwar region, the average annual rainfall varies significantly, ranging from 492 mm in the lowland region to 1710 mm in the high-altitude region, demonstrating a substantial difference over a relatively small area (Hussain et al., 2021). The abrupt changes in precipitation trends are influenced by various factors, including elevation, latitude, and proximity to water bodies. For example, the Precipitation Concentration Index (PCI) and Concentration Index (CI) reveal higher values in the country's dry and hot zones, with a linear relationship between these indices and latitude and altitude (Zaman et al., 2023). Similarly, Hanif et al. (2013) observed an increase in high-latitude precipitation across the country, while no significant patterns were observed in the low-latitude region.

Pakistan is among the most vulnerable countries to the impacts of climate change (Ahmed et al., 2018). The severe rainfall in August 2022 led to devastating floods in Pakistan, impacting agriculture, infrastructure, and causing human and livestock fatalities. The rainfall on August 17 to 18 was unusually heavy, resulting in flooding in the southern provinces (Malik et al., 2023). An analysis of climate data from 1990-2022 signifies increased precipitation in Sindh (+30 to +60 mm) and Punjab (+100 to 300 mm), with monsoon increases of approximately 50 to 200 mm (Qureshi et al., 2023). While this may reduce the use of freshwater for agriculture, it also intensifies the risks of flooding, waterlogging, and soil salinization. A study from 1979-2020 identified increasing precipitation patterns across various indices, with notable rises in total and maximum 5-day precipitation. Northern and sub-humid agro-ecological zones observed more precipitation (Hina et al., 2024), underscoring changes in Pakistan's rainfall patterns. The 2022 flooding, caused by extreme monsoon rainfall, was the worst in the country's history. Both models and observations suggest intensified rainfall as Pakistan's climate warms (Otto et al., 2023). The Upper Indus Basin, vital for Pakistan's water resources, is expected to experience a 13-17% increase in precipitation patterns in the future, leading to a significant upsurge in streamflow by 19-30% (Haleem et al., 2023). These variations in precipitation and streamflow patterns will have significant implications for hydroelectricity generation, irrigation, and flood prevention. A study analyzing rainfall data from 1980-2019 found that El Niño events exacerbate drought severity in Pakistan (De Oliveira-Júnior et al., 2022), explaining the complex association between climate patterns and local precipitation. Climate change is a critical global issue as the Earth's temperature rises by 4 °C due to the accumulation of greenhouse gases (Gisbert et al., 2018).

The main objectives of this study are outlined as follows: (i) To identify significant change points in each grid point time series during the long-term precipitation period (1951-2019), with a particular focus on how these change points vary across different seasons. This analysis will provide insights into the seasonal variations in precipitation changes over time. (ii) To investigate differences in precipitation patterns across the country on both temporal and spatial scales for the two periods, 1951-2019 (long-term) and 1981-2019 (short-term). This point emphasizes understanding how precipitation patterns vary over time and space between the two specified periods, with an underlying context of climate change effects observed from 1981 onwards. (iii) To investigate the differences in trends in precipitation between the two periods, focusing specifically on how these trends compare in both the long-term and short-term contexts.

This research adds value to the current body of literature by offering a grid-scale spatiotemporal assessment of the variation in precipitation in Pakistan through two temporal periods (1951-2019 and 1981-2019). This is in contrast to earlier works that mainly do regional or station based analysis whereby this study combines the change-point detection of Pettitt with the trend analysis in order to detect both structural and directional change in the precipitation patterns. Moreover, the results are explained with respect to sustainable development as the relationship between precipitation variability and water resource management, agricultural productivity, and disaster risk is provided, thus providing policy-relevant information on climate sensitive areas. We have provided illustration of the provincial locations of all the districts under study in Pakistan, along with their names and short names (SN), including the regions of GB, Azad Kashmir (AK), Fata (FATA), and the Federal Capital Territory, Islamabad (ISB) in Figure 1.

2. Data and Method

We considered the weather patterns in Pakistan from 1951 to 2019 by using the Global Precipitation Climatology (GPCC) dataset (Rudolf and Schneider 2005; Schneider et al. 2008). This dataset is compiled from ground-based observations. This dataset offers detailed precipitation estimates at a spatial resolution of 0.25 degrees' latitude by 0.25 degrees' longitude. The GPCC dataset is widely recognized for its reliability and is frequently used in studies requiring high-resolution precipitation information, as highlighted by Gupta et al. (2024) and Raziei et al. (2011). This dataset had information about rainfall across different parts of the country on a monthly and seasonal basis. According to Schneider et al. (2017), the 2015 dataset from the GPCC offers precipitation climatology data spanning from 1951 to 2000. Utilizing climatological normals derived from around 75,100 rain gauges, this dataset facilitates the assessment of average land surface precipitation as a component of the global water cycle.

Pettitt's test, a modified form of the Mann–Whitney test (Pettitt, 1979), is used to determine the exact point at which a change in the median of a time series occurs.

PROVINCE	DISTRICT	SN
PUNJAB	Punjab	PJ
PUNJAB	Bhakkar	BK
PUNJAB	Muzaffargarh	MH
PUNJAB	Islamabad	FCT
PUNJAB	Sialkot	ST
PUNJAB	R Y Khan	RN
PUNJAB	Rawalpindi	RI
PUNJAB	Rajanpur	RP
PUNJAB	Pakpattan	PK
PUNJAB	Okara	OK
PUNJAB	Narowal	NL
PUNJAB	Jhelum	JM
PUNJAB	Gujrat	GT
PUNJAB	Gujranwala	GA
PUNJAB	D G Khan	DG
PUNJAB	Chakwal	CH
PUNJAB	Bahawalpur	BR
PUNJAB	Attock	AK
PUNJAB	Lahore	LO
BALOCHISTAN	Balochistan	BL
BALOCHISTAN	Dera Bughti	DB
BALOCHISTAN	Harnai	HI
BALOCHISTAN	Nasirabad	NB
BALOCHISTAN	Kachhi	KCI
BALOCHISTAN	Awaran	AW
BALOCHISTAN	Khuzdar	KR
BALOCHISTAN	Killa Abdullah	QD
BALOCHISTAN	Killa Saifullah	QS
BALOCHISTAN	Lasbela	LSB
BALOCHISTAN	Mastung	MU
BALOCHISTAN	Panjgur	PJ
BALOCHISTAN	Pishin	PI
BALOCHISTAN	Zhob	ZB
BALOCHISTAN	Ziarat	ZT
BALOCHISTAN	Quetta	QA
BALOCHISTAN	Sibi	SI
SINDH	Ghotki	GH
SINDH	Jacobabad	JD
SINDH	Larkana	LRK
SINDH	Naushahro Feroz	NF
SINDH	S. Benazirabad	SBD
SINDH	Shikarphur	SKP
SINDH	Sukkur	SK
SINDH	T. A Yar	TAY
SINDH	Thatta	TA
SINDH	Dadu	DU
SINDH	Jamshoro	JS
SINDH	Tharparkar	TPK
SINDH	Karachi	KHI
SINDH	Hyderabad	HD
KPK	Bannu	BU
KPK	Khyber Pakhtunkhwa	KP
KPK	Buner	BD
KPK	Chitral	CL
KPK	Hangu	HG
KPK	Karak	KK
KPK	Shangla	SH
KPK	Upper Dir	DP
KPK	Lower Dir	DL
	Azad Kashmir	AK
	Fata	FT
	Gilgit Baltistan	GB
	Jammu Kashmir	JK

Fig. 1 Spatial distribution of the study area showing administrative districts of Pakistan along with their corresponding abbreviations. The map includes all major regions, including Gilgit-Baltistan (GB), Azad Kashmir (AK), Federally Administered Tribal Areas (FATA), and Islamabad Capital Territory (ICT), used for spatial analysis

This nonparametric rank test is commonly applied to identify a single change point in a time series (Aksu et al., 2022). We applied this test to each grid point time series to investigate the point at which the median changes in the long-term series for each season.

The Modified Mann-Kendall (MMK) test was used to consider the possibility of serial autocorrelation in the time series of precipitation (Hamed and Rao, 1998). The method modifies the variance of the MK test (Mann, 1945; Kendall, 1955; Lettenmaier et al., 1994; Molnár and Ramírez, 2001; Birsan et al., 2005) to minimize the effect of autocorrelation and thus the trend is better detected. At every grid point, the MMK test was used to determine the direction and statistical significance of the precipitation trends over the study area.

As explained earlier, we applied the MMK trend test to identify precipitation trends in Pakistan using gridded time series data. The analysis was conducted at each grid point (longitude-latitude) within the geographical domain of the country across two temporal domains. The results include composite maps of precipitation and MMK trend test statistics values at each grid point, providing a seasonal-scale view of the spatial distribution of precipitation trends across different periods in the country.

The acquired results were assessed at a significance level of $p < 0.05$. The null hypothesis H_0 was rejected, signifying the existence of either an upward or downward trend in the dataset, aligning with the explanation provided by Blain (2012). The test is mathematically explained by De Jongh et al. (2006) as follows: if v_j and v_k represent independent and identically distributed random data entries, the test statistic 's' is written as

$$s = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(v_j - v_k) \quad \text{..... (1)}$$

Where the sign function $sgn\ (v)$ is given below,

$$sgn\ (v) = \begin{cases} 1 & when\ v > 0 \\ 0 & when\ v = 0 \\ -1 & when\ v < 0 \end{cases} \quad \text{..... (2)}$$

For a sample size of 30 or more, testing of the hypothesis can be applied using the given test statistic, with 'z' denoting the standard normal deviation's magnitude.

$$z = \begin{cases} \frac{s-1}{\sqrt{m}} when\ s > 0 \\ 0 \quad when\ s = 0 \\ \frac{s+1}{\sqrt{m}} when\ s < 0 \end{cases} \quad \text{..... (3)}$$

In the MMK test at a 95% significance level, a test statistic above 1.96 points to a substantial surge in precipitation at the corresponding grid position in Pakistan. Conversely, a value below -1.96 suggests a significant decrease in precipitation at that grid location. If the value falls within the range of -1.96 to 1.96 at any grid point within Pakistan, it is interpreted as indicating no significant decrease or increase in precipitation. A test statistic of zero reveals that there is no trend in precipitation. This technique of presenting the results on composite maps is also used in (Rehman et al., 2019a, b).

If "N" represents the sample size, and m represents the variance of s, then we can write,

$$m = \frac{N(N-1)(2N+5) - \sum_{i=1}^{C} D_i(D_i - 1)(2D_i + 5)}{18} \quad \text{..... (4)}$$

Here, C is the total number of collections of values v_i that have identical peaks (i.e., draws), and the total number of draws in the ith collection is signified by *D*i.

It is important to note that this study focuses on identifying the direction and statistical significance of precipitation trends rather than quantifying their magnitude. Therefore, Sen's slope estimator was not incorporated, as the primary objective is to highlight spatial patterns of increasing or decreasing trends relevant to climatic variability and associated risks.

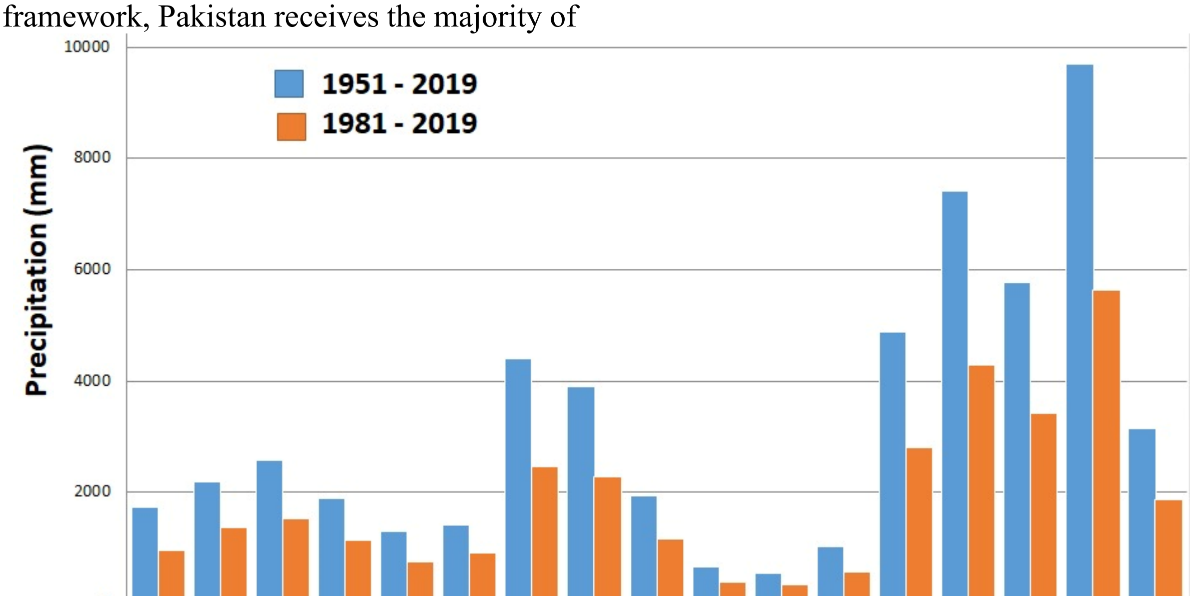
3. Results and Discussions

Pakistan experiences four distinct seasons throughout the year: Summer (June to August, JJA), autumn (September to November, SON), winter (December to February, DJF), and spring (March to May, MAM). Additionally, an extra season considered in this study is the cool season, spanning from December to March.

Figure 2 illustrates the distribution of total precipitation over monthly and seasonal time scales for both periods. It is evident from this figure that, during the short-term period, precipitation in all study seasons consistently exceeds half of the precipitation received during the long-term period.

In a monthly analysis, the months of July and August emerge as major contributors to precipitation in both scenarios, while the lowest precipitation levels are typically observed in November. When considering the standard four-season framework, Pakistan receives the majority of its precipitation during summer, followed by spring, winter, and autumn. A significant proportion, specifically about 60% of the overall precipitation, takes place during the monsoon season (June to September) (Hanif et al., 2013), while around 30% of the total precipitation receives during the winter months (Asmat and Athar, 2017). These trends are consistently visible in Figure 2, which also highlights the lowest monthly precipitation levels typically occurring in November and December.

Figure 3 depicts an overview of seasonal trend analysis across both temporal scales. All seasons show precipitation has high variations. In all seasons during the long-term scenario, positive slopes suggest increased precipitation. However, it's notable that this escalation, as per the MMK test, is not statistically considerable at the 5% significance level. The most noteworthy rise in precipitation is observed through the summer and autumn seasons (Figure 3d and e), collectively known as the monsoon season.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	DJFM	MAM	JJA	SON
1951-2019	1731.1	2178.8	2577.7	1893.5	1306.3	1402.8	4393.4	3902.1	1941.1	662.63	549.82	1020	4873.6	7405.8	5777.4	9698.2	3153.6
1981-2019	956.24	1359.9	1536.2	1140.7	744.94	903.34	2465.1	2269.7	1155.4	392.84	330.66	570.95	2809	4285.2	3421.8	5638.1	1878.9

Fig. 2 Monthly and seasonal distribution of total precipitation across Pakistan for the long-term (1951–2019) and short-term (1981–2019) periods. The figure highlights the dominance of monsoon precipitation (June–September) and comparatively lower precipitation during winter and autumn months.

On the short-term scale, a notable decrease in precipitation was during the winter, cool, spring, and summer, with the autumn season showing the most substantial increase. The maximum decrease was observed during the cool and spring season. It's worth mentioning that all these fluctuations in precipitation are statistically insignificant.

Considering the winter season before 1981 in Figure 3(a), only three instances show peaks in precipitation that surpass the 100mm threshold, while six events exhibit precipitation levels below 50mm. In contrast, during this period, 11 events are characterized by less than 50mm of precipitation, and four events exceed 100mm, including the year 2004, which represents the highest precipitation, and 2000, which marks the lowest precipitation year in the study period. This pattern suggests a potential decreasing trend in winter precipitation. Safdar et al. (2023) also assessed a substantial declining trend in winter precipitation over Pakistan, mostly in the western mountainous regions of Pakistan.

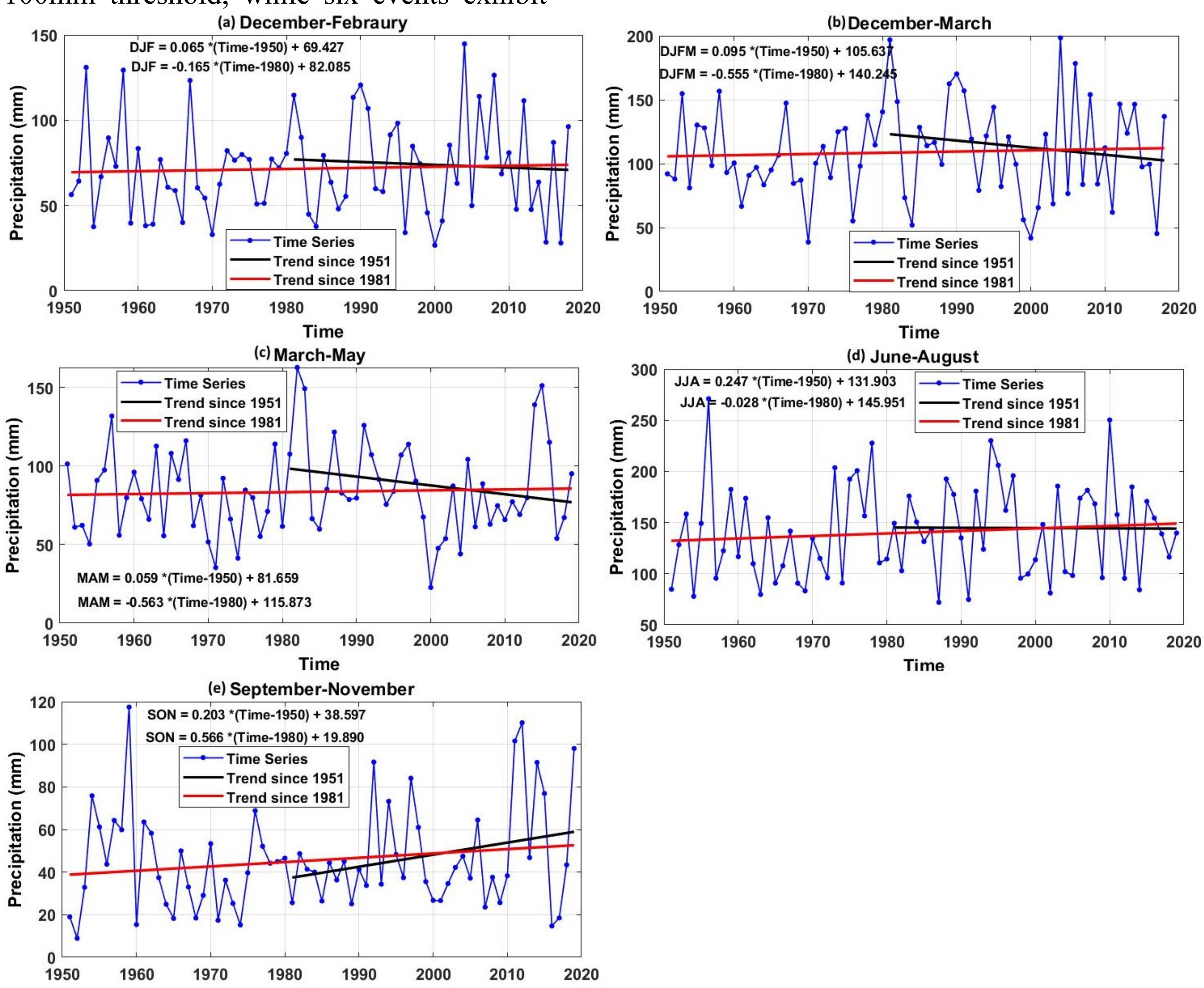


Fig. 3 Seasonal temporal trends in precipitation for long-term (1951–2019) and short-term (1981–2019) periods: (a) winter (DJF), (b) cool season (DJFM), (c) spring (MAM), (d) summer (JJA), and (e) autumn (SON). Trend lines represent changes in precipitation over time, with corresponding slope values indicating the direction and magnitude of variation.

Figure 4 illustrates the terrain elevation (in meters) of Pakistan. You can find the towering peaks of the Himalayas and Karakoram chains in the north of the state. According to Iqbal et al. (2018), the topographical effect has a significant impact on the precipitation pattern over Pakistan. Specifically, there is a positive correlation between elevation and precipitation, meaning that higher elevations tend to receive more rainfall. It's noteworthy that both elevation and latitude play crucial roles in influencing the intensity and quantity of precipitation in Pakistan. This weather phenomenon is commonly referred to as orographic influence (Dimri et al., 2015; Rehman et al., 2019). Pakistan experiences an arid climate, characterized by hot summers and cool to cold winters. The country shows noteworthy deviations in both precipitation and temperature extremes over different locales due to its differing landscape and terrain, which changes from north to south.

Figure 5 presents the results of Pettitt's test for the winter season. A significant change in median precipitation from 1951 to 1980 was observed across most of the Jammu and Kashmir (JK) regions, the western coastline tip of BL and some locations near the southern coastline of PJ (Figure 5a). In contrast, after 1981, significant changes in median precipitation totals during winter were evident in the northern regions of JK and GB, the northern areas of FATA, the northern and southern coastlines of Balochistan (BL), and the southern part of KP including some locations near to the southern coastline of Sindh (Figure 5b).

The results of Pettitt's test for the cool season indicate that from 1951 to 1981, significant changes in median precipitation occurred in southern BL, southern KP, northern GB, and many parts of JK (Figure 6a). In contrast, from 1981 to 2019, many parts of regions experienced significant changes in median precipitation, particularly in the southern areas of KP and FATA, as well as parts of the northern and southern coastlines of BL (Figure 6b).

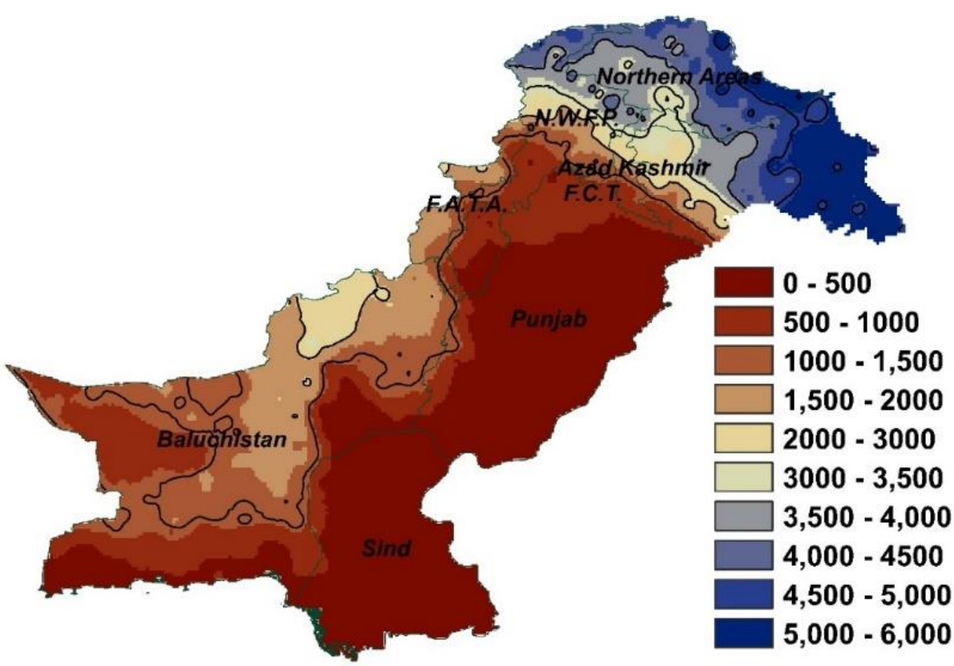


Fig. 4 Elevation map of Pakistan illustrating the topographic variation across the study region. Higher elevations in the northern regions (Himalayas, Karakoram, and Hindu Kush ranges) contrast with lowland plains in Punjab and Sindh and arid regions in Balochistan, highlighting the role of orographic effects in precipitation distribution.

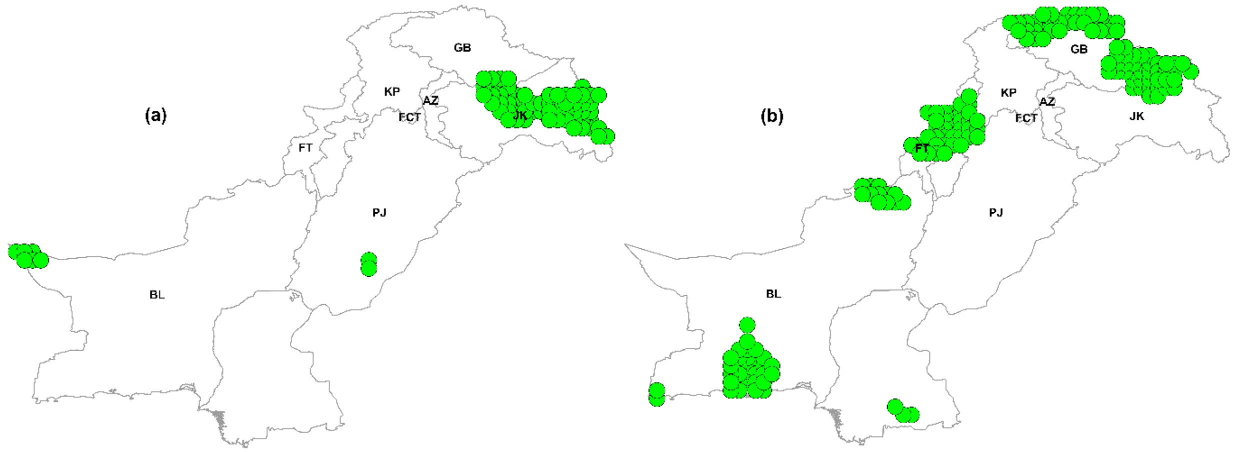


Fig. 5 Spatial distribution of significant change points in median winter precipitation (DJF) identified using Pettitt's test for (a) 1951–1980 and (b) 1981–2019. The maps indicate regions where statistically significant shifts in precipitation regimes occurred during the respective periods.

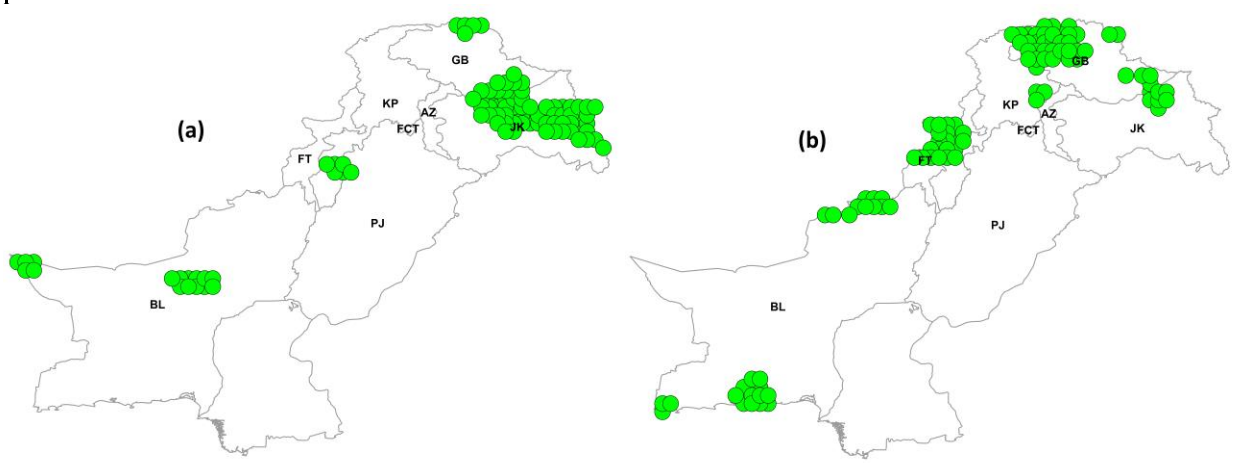


Fig. 6 Spatial distribution of significant change points in median cool-season precipitation (DJFM) identified using Pettitt's test for (a) 1951–1980 and (b) 1981–2019, highlighting temporal shifts in precipitation patterns across different regions.

The results of Pettitt's test for the spring season show that between 1951 and 1981, significant changes in median precipitation were observed along the western border and northeastern areas of BL near the Sindh border, the northern regions of KP, the northeastern border of PJ, and some northern areas of AZ (Figure 7a). In contrast, from 1981 to 2019, significant changes in median precipitation occurred in many parts of northern KP, AZ, BL, FATA, as well as the central regions of BL and southern PJ near the Sindh coastline (Figure 7b).

The results of Pettitt's test for the summer season indicate that between 1951 and 1981, significant changes in median precipitation were observed along the northern and northeastern border of PJ, the Federal Capital Territory (FCT), southern KP, the northern GB, the northeastern border of Balochistan (BL) and adjoining areas of PJ, as well as some locations along the western border of BL (Figure 8a). The summer season exhibits more significant changes compared to other seasons during this period. In contrast, from 1981 to 2019, significant changes in median precipitation were observed in many regions along the western border of BL and the northern areas of FATA and GB (Figure 8b).

The results of Pettitt's test for the autumn season indicate that between 1951 and 1981, significant changes in median precipitation were primarily observed in BL, particularly along its western border, adjoining areas, and the southeastern border with Sindh. Notably, Karachi was also part of this change, along with some areas along the central and eastern borders of PJ (Figure 9a). In contrast, from 1981 to 2019, significant changes in median precipitation were observed in northern GB and KP. South of FATA, this pattern extended to central PJ, southern BL, and, interestingly, the southeastern tip of Sindh (Figure 9b). The western disturbance (WD) is a well-known weather system in South Asia that typically occurs from November to February. It originates from cyclonic storms over the Mediterranean Sea (Asmat and Ather, 2017) and interacts with the subtropical western jet in the mid-latitude region. According to Dimri et al. (2015), the WD plays a crucial role in influencing winter (December-February) precipitation patterns, particularly in the northern highlands of Pakistan.

Upon comparing Figures 10a-c), it becomes evident that there is a decrease in precipitation in the GB region.

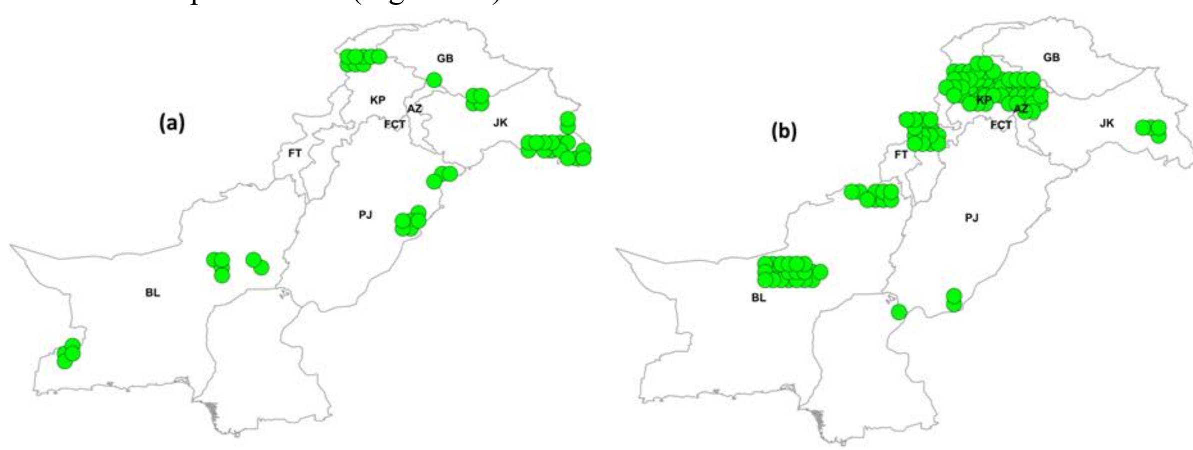


Fig. 7 Spatial distribution of significant change points in median spring precipitation (MAM) identified using Pettitt's test for (a) 1951–1980 and (b) 1981–2019, indicating regions with notable temporal changes in precipitation behavior.

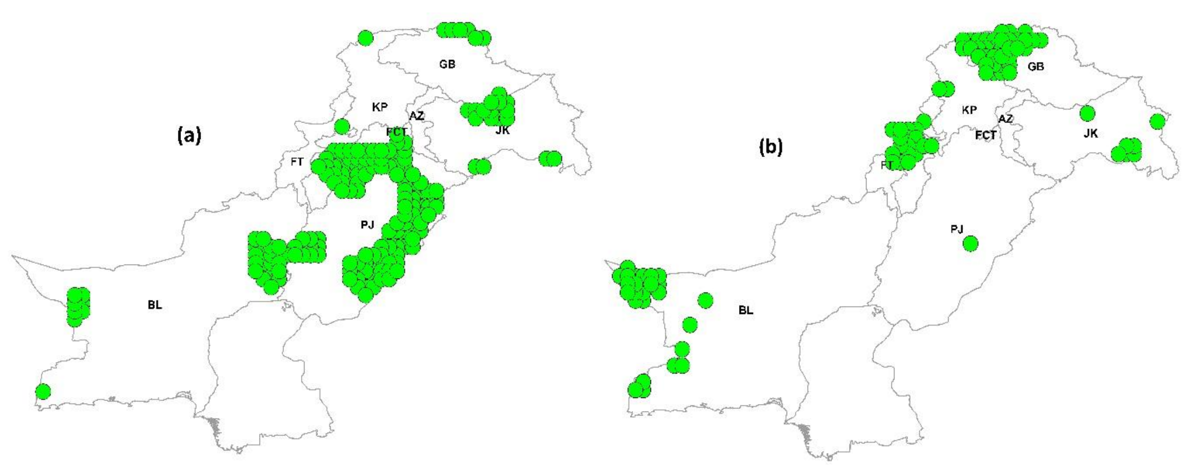


Fig. 8 Spatial distribution of significant change points in median summer precipitation (JJA) identified using Pettitt's test for (a) 1951–1980 and (b) 1981–2019, showing areas with statistically significant shifts associated with monsoon dynamics.

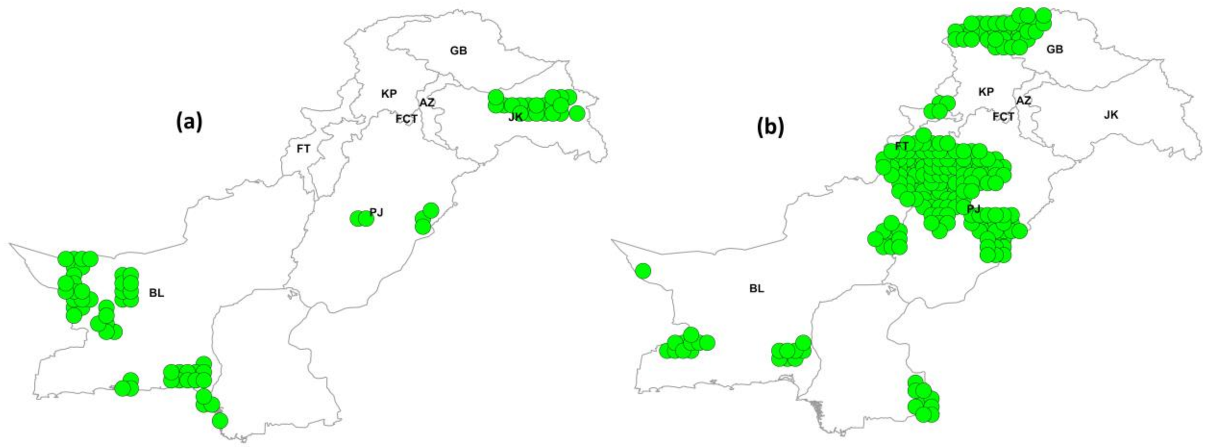


Fig. 9 Spatial distribution of significant change points in median autumn precipitation (SON) identified using Pettitt's test for (a) 1951–1980 and (b) 1981–2019, highlighting spatial variations in precipitation regime shifts

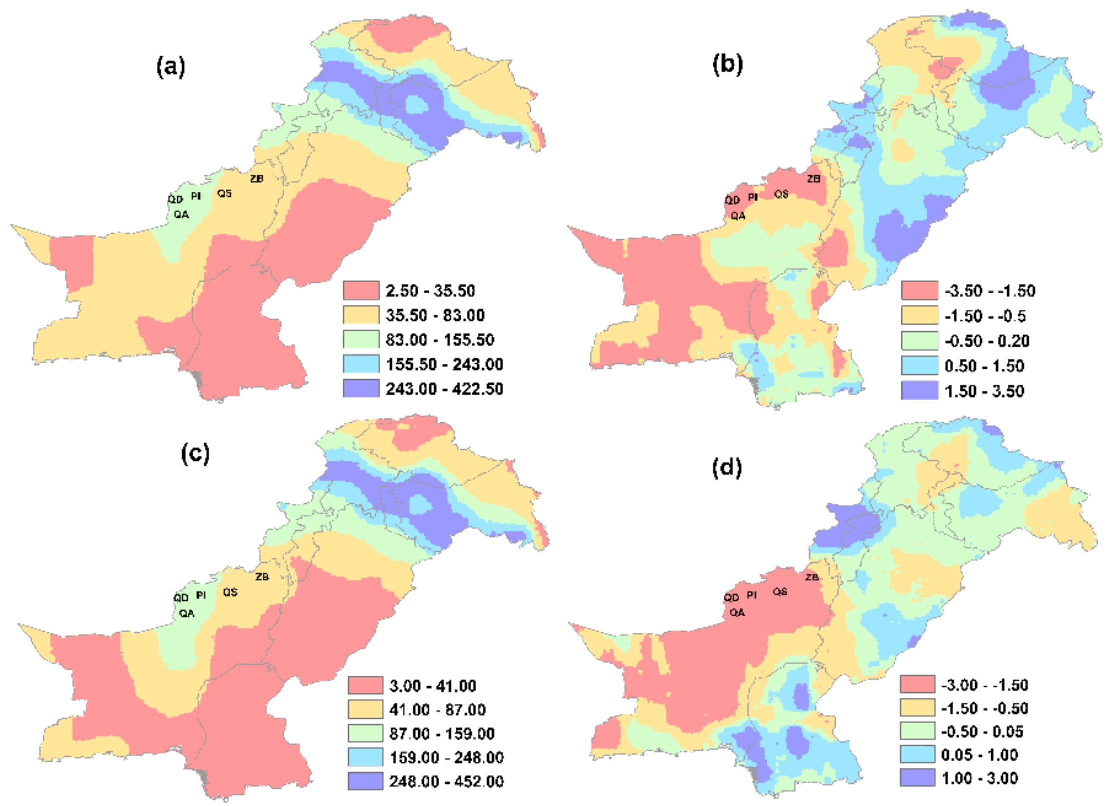


Fig. 10 Spatial distribution of winter (DJF) precipitation and trend patterns across Pakistan: (a) long-term total precipitation (1951–2019), (b) long-term Modified Mann–Kendall (MMK) trend, (c) short-term total precipitation (1981–2019), and (d) short-term MMK trend. Positive values indicate increasing trends, while negative values indicate decreasing trends

This result is consistent with the results of Iqbal et al. (2019), which revealed a decline in winter precipitation (ranging from 0 to -0.25 mm/year) over the western region of the Himalayan region in GB.

The country received relatively less precipitation during the winter months (December-February) in the short time frame while the precipitation totals remained in the range of 3mm to 35mm in Sindh, southern Punjab, and adjacent districts in the long term

(Figure 10a). In contrast, during the short term (Figure 10c), these regions observed precipitation ranging from 1mm to 15mm.

Figure 10 also reveals the northwest region of BL, including areas such as ZB, QD, PI, north QA, and northwest QS, which exhibit a significant decreasing trend in precipitation during the long term (Figure 10b). Furthermore, the areas characterized by a significant decrease in precipitation extend further south in the short-term period (Figure 10d). These findings align with the results reported by Safdar et al. (2023).

Moving to the northern areas of PJ, there was a higher precipitation range of 35mm to 160mm in the long-term and 15mm to 50mm in the short-term scenario. This precipitation pattern appears to follow the terrain elevation, with lowland areas in the south receiving less precipitation compared to the highland areas in the north of Punjab. This result of orographic influence is aligned with the findings of Iqbal et al. (2018).

In the north of KP, at elevations ranging from 600m to 6650m, the districts received the highest precipitation totals, ranging from 160mm to 430mm during the long term (Figure 10a). However, during the short term (Figure 10c), the same areas received comparatively less precipitation, ranging from 50mm to 150mm. Notably, in both terms, an irrelevant decline in precipitation is perceived.

Joshi et al. (2013) revealed a survey according to which the herders of GB had observed variations in the climate over the past 10-15 years. These variations included protracted and more severe droughts during the summer, increased instances of heavier snowfall in the winter, and extended summers along with shorter winters.

Figure 11 presents a profile of cool-season precipitation across the study districts during both periods.

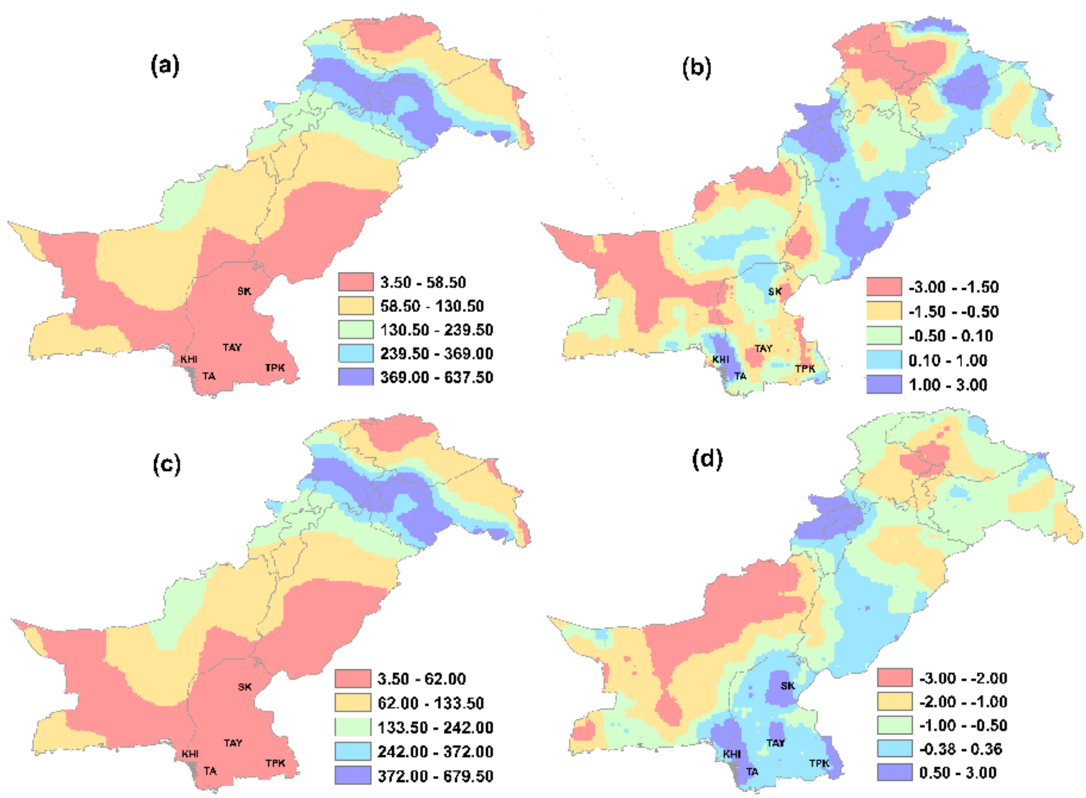


Fig. 11 Spatial distribution of cool-season (DJFM) precipitation and trend patterns across Pakistan: (a) long-term total precipitation (1951–2019), (b) long-term MMK trend, (c) short-term total precipitation (1981–2019), and (d) short-term MMK trend. The maps highlight regional variations in precipitation intensity and trend direction

Notably, the precipitation over these districts has increased compared to what was observed during the winter season (Figure 10). This increase in precipitation has achieved statistical significance at the 5% significance level in the southern districts of KP, except for the region near the southern tip of the political boundaries with Baluchistan. This trend is consistent during both time intervals, and there is also an enhancement in precipitation during the short-term period.

Conversely, the northern districts of KP show a statistically significant decrease at the 5% significance level, but there is an insignificant increase in precipitation in this region during the short-term interval (Figures 11(a and d)). Additionally, there is an insignificant increase in precipitation observed in the southeast districts of Punjab, covering a smaller area compared to the long-term interval (Figure 11(b and d)).

As we move towards Sindh, the results obtained in Figure 11(d) indicate a significantly increasing trend in precipitation that covers a larger area compared to the winter season, particularly during the short-term time interval (Figure 10d). These trends are prominent in the northern areas of Sindh, including SK, in central Sindh covering TAY and MPK, in the southwestern tip encompassing TA and KHI (excluding the southeast region of KHI), and in the southeast of TPK, situated at the southeastern tip of Sindh (Figure 11d). Overall, the distribution of precipitation in the country remains consistent in both terms, as shown in Figure 12 (a and d). Notably, there is relatively more precipitation during the short-term scenario in Spring (March-May).

In both terms, the districts highlighted in red contours in BL, Sindh, and the southeast of PJ received precipitation ranging from 6mm to 55mm (Figure 12a and c).

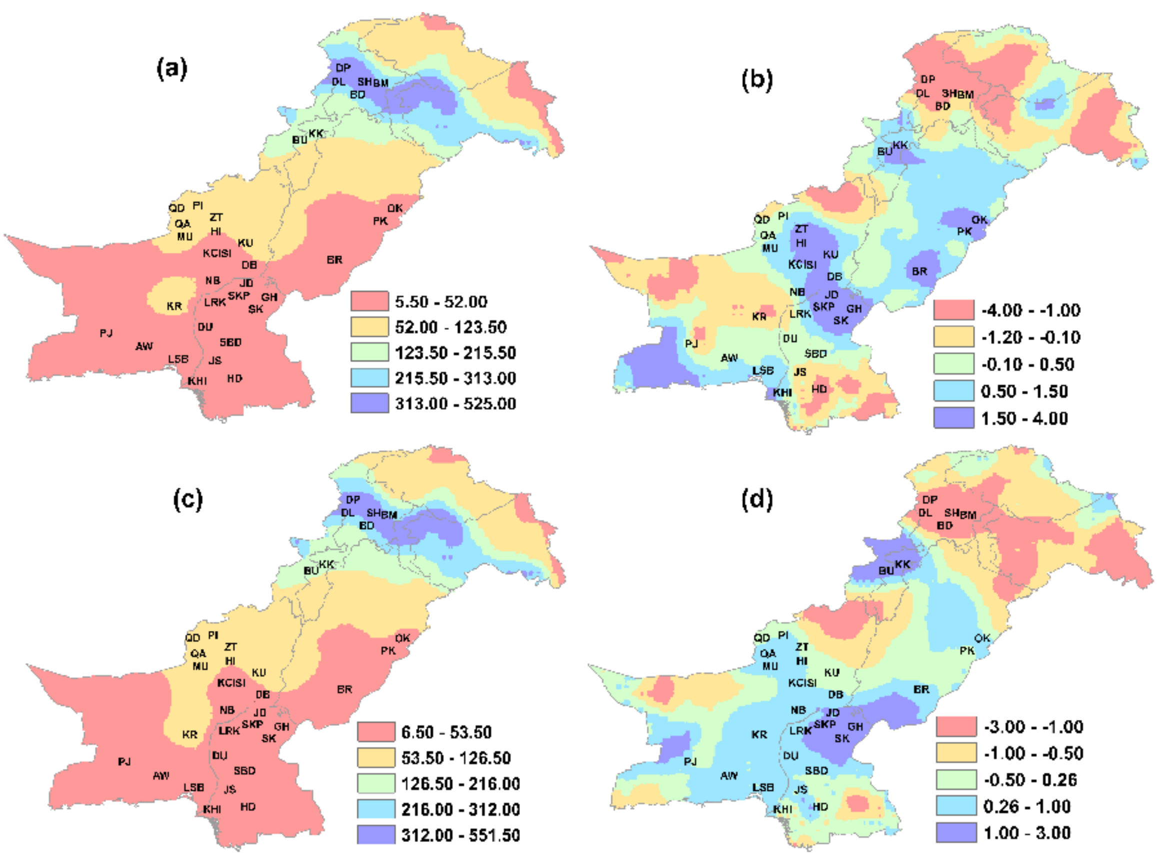


Fig. 12 Spatial distribution of spring (MAM) precipitation and trend patterns across Pakistan: (a) long-term total precipitation (1951–2019), (b) long-term MMK trend, (c) short-term total precipitation (1981–2019), and (d) short-term MMK trend, illustrating seasonal variability and regional differences

Specifically, the southern district of Kech and the northern districts of DB, KU, SI, KCI, and HI in BL have observed a significant increasing trend in long-term precipitation (Figure 12b). Conversely, regions including AW, LSB, KR, NB, western PJ, MU, QA, southern QD, southern PI, and western ZT have witnessed an increasing but insignificant trend, except for Kech, where an insignificant decreasing trend is observed in the short-term (Figure 12d).

Moving to northern Sindh, districts such as SK, SKP, GH, and JD have shown a noteworthy increasing inclination in precipitation, while the rest of the province has endured a minor decline (Figure 12b). In the short-term scenario, the significant increasing trend extends to the KPK district, while the insignificant increasing trend persists in LRK, DU, NF, SBD, JS, and western HD in Sindh.

The districts in northern KP, including CL, DP, BM, SH, DL, BD and adjacent regions of FATA, receive the highest precipitation totals, ranging from 215mm to 550mm (Figure 12a and c). However, these areas have received more precipitation during the short-term period. Unfortunately, these districts bear significant decreasing trends, except for central FATA and the southern districts of KP, such as KK, and BU, where a significant increasing trend is observed during both time spans (Figure 12b and d).

Across PJ, the majority of districts exhibit an insignificant increasing trend in precipitation during the long term. However, in the southeast, districts such as PK, OK, SI, and northern BR experience a significant increasing trend (Figure 12b). Additionally, a strip of districts extending from the southeast to the northwest of Punjab shows an insignificant increasing trend. Meanwhile, districts situated at the southeastern tip, adjacent to Sindh, also exhibit an increasing trend that stretches from RN to BR during the short-term period (Figure 12d).

Low-pressure systems over the Bay of Bengal are associated with summer precipitation in Pakistan, particularly during the monsoon season from July to September (Asmat and Ather, 2017). This period is generally denoted by the monsoon depression. The combination of summer precipitation during the monsoon season and the melting of snow from the northern mountains contributes to flash flooding in the country. Pakistan, being primarily an agricultural nation, with approximately 70% of its population residing in rural areas, is highly susceptible to crop damage caused by flash floods and pest attacks (Fahad and Wang, 2018; Fahad and Jing, 2018). Safdar et al. (2019) revealed that monsoon rainfall over Pakistan has declined, the temperature patterns have increased significantly, and a southward shift in overall rainfall occurrence and an eastward shift in moderate to heavy rainfall patterns during 2010 to 2017 indicate changing monsoon dynamics.

Figure 13 illustrates that Punjab province received precipitation ranging from 80mm to 575mm in both time scenarios, with significant differences in observed trends. In the long-term perspective, most of the districts exhibit an increasing trend in rainfall. Specifically, districts in the southwest, such as RN, DG, and MH, and those in the north, including AK, RI, JM, GT, ST, and NL, show stable trends. However, the northern part of district RP shows a stable trend.

Conversely, in the northwest of Punjab, south of DG, northwest of RP, and in the north of Punjab, districts like AK, RI, JM, CH, GT, ST, NL, LO, OK, and PK show stable trends. The rest of the districts observed increasing trends during the period from 1980 to 2019.

Precipitation in the KP and FATA regions ranged from 80mm to 350mm in both time spans. Figure 13 illustrates significant precipitation trends over southern KP and adjacent areas of FATA. Notably, a significant increasing trend is observed in regions like KK, HG, BU, and their adjoining areas in FATA during the short-term interval.

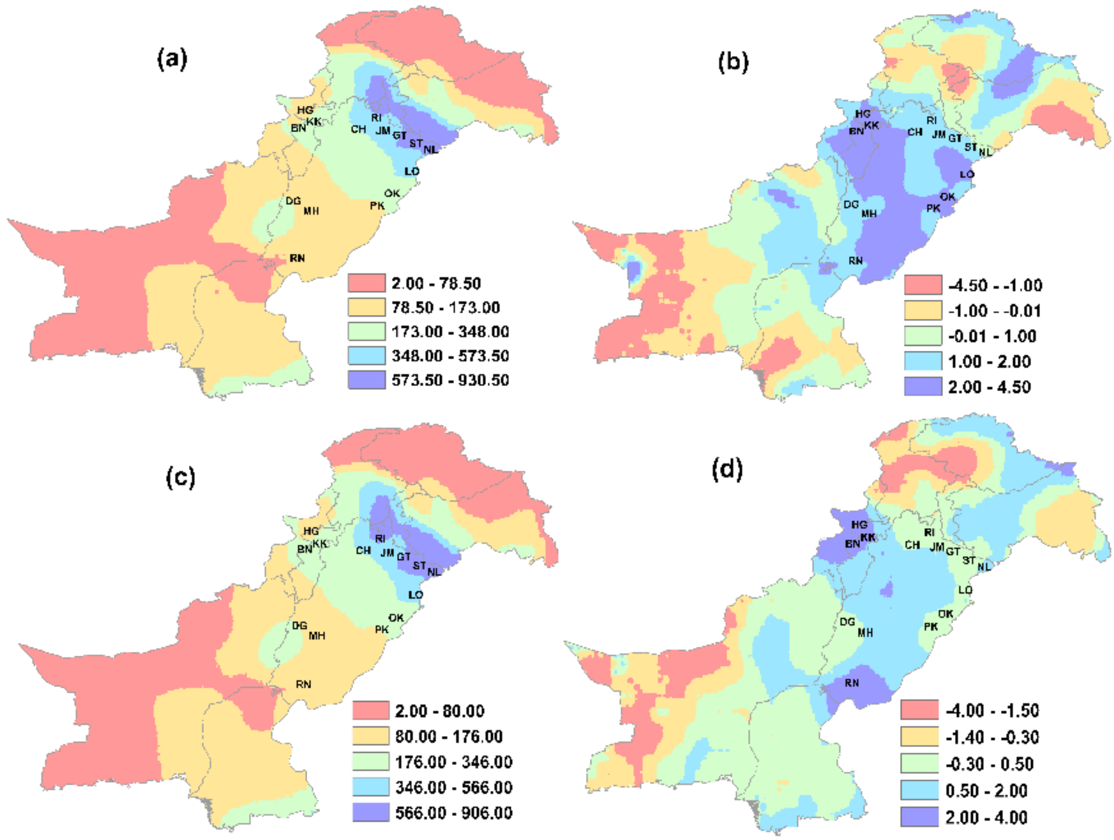


Fig. 13 Spatial distribution of summer (JJA) precipitation and trend patterns across Pakistan: (a) long-term total precipitation (1951–2019), (b) long-term MMK trend, (c) short-term total precipitation (1981–2019), and (d) short-term MMK trend. The results reflect the influence of monsoon systems on precipitation variability

The majority of the districts in BL received precipitation ranging from 3mm to 80mm, primarily in western Baluchistan. In contrast, the northeastern and southeastern districts of Baluchistan, including Sindh, received 80mm to 180mm of rainfall in both scenarios. Meanwhile, the northern parts of Sindh experienced precipitation levels ranging from 3mm to 80mm. Notably, all regions with red colour contours in Figure 13 (b and d) show stable trends in both terms.

According to a literature review conducted by Fahad et al. (2020), farm households in dryland regions tend to experience more pronounced climate variations when compared to their counterparts in wetland areas. In a comparative analysis, it is observed that during the short-term period, precipitation in GB areas shows a slight increase (Figure 13c). These findings are consistent with the study conducted by Iqbal et al. (2019), which revealed that the upper part of the Himalaya region in GB experiences an increase in summer precipitation at a rate of 0.25-1.25 mm per year.

According to Latif et al. (2017), the summer monsoon rainfall (June-September) over South Asia exhibits a dipole pattern, with increasing rainfall over Pakistan and decreasing rainfall over central and north India, especially during July and August, due to the weakening of northward moisture transport over the Bay of Bengal. The low-pressure system over the Arabian Sea during spring and April-June is responsible for the precipitation over the south coast of the country (Asmat and Ather, 2017). According to Adeel et al. (2024), the Arabian Sea surface temperature (SST) is associated with the rainfall variability during the summer (July-September) monsoon over Pakistan and South Asia. Figure 14 (a and c) illustrates that precipitation patterns across the county remain similar, with minor variations in high-precipitation regions, indicated by the dark blue colour. In Figure 14 (b and d), the districts represented by dark blue contours exhibit significant increasing trends over the specified periods, while the light blue regions indicate insignificant increasing trends. The districts specified in the remaining colour variants experienced insignificant decreasing trends over the same time.

Figure 14 also illustrates significant variations in precipitation. It shows a statistically significant increase in precipitation over the southern regions of KP and adjacent areas of FATA during the long-term period. However, during the short-term period, there appears to be a decrease in this region (Figure 14).

Furthermore, Figure 14c depicts a decline in precipitation in BL, while a positive inclination is detected in the southeastern tip of Sindh when compared to the long-term interval (Figure 14a).

Comparatively, the highest precipitation, ranging from 105mm to 430mm, occurs during Autumn in the northernmost regions (Figure 14a and c), extending further south to adjacent districts in PJ during summer (Figure 13a and c). This pattern is consistent across both time intervals in the country. In the western mountainous region of BL, during Autumn in the long-term interval (Figure 14a), precipitation falls in the range of 85mm to 160mm but remains statistically insignificant.

It is noticeable through the spatial trend analysis, as depicted in Figures 10-14. In many districts, the trends in total precipitation exhibit statistical significance, and these findings are in line with previous research, such as Younus et al. (2023) and Khan et al. (2022), who utilized regional meteorological weather station datasets.

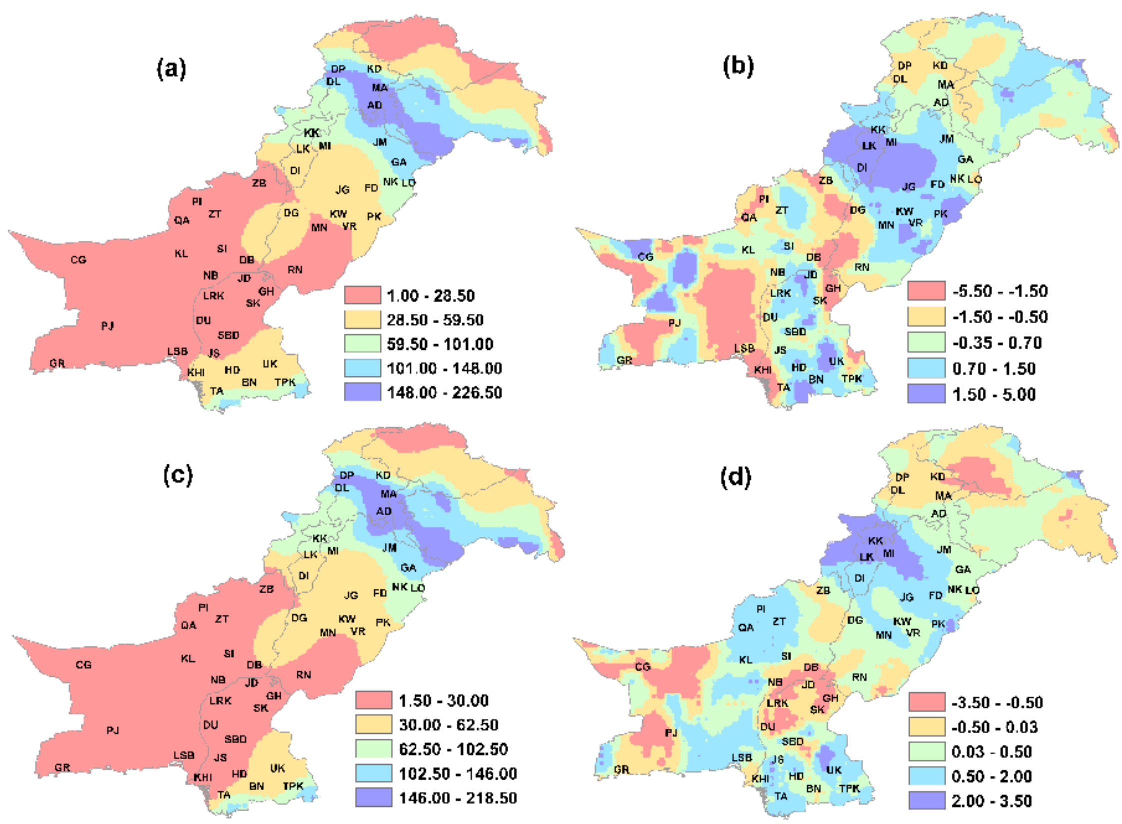


Fig. 14 Spatial distribution of autumn (SON) precipitation and trend patterns across Pakistan: (a) long-term total precipitation (1951–2019), (b) long-term MMK trend, (c) short-term total precipitation (1981–2019), and (d) short-term MMK trend, highlighting spatial differences in precipitation trends during the post-monsoon season

Furthermore, the observed spatial variability in precipitation trends can be attributed to key atmospheric and geographical drivers. Monsoon dynamics play a dominant role in summer precipitation, particularly influenced by low-pressure systems over the Bay of Bengal. Additionally, western disturbances significantly impact winter precipitation in northern regions. Orographic effects further intensify precipitation in high-altitude areas such as the Himalayas and Karakoram ranges. The increased variability observed after 1981 is also consistent with documented extreme rainfall events and flood occurrences in Pakistan, indicating a shift toward more unstable precipitation regimes.

4. Conclusion

This study examined the spatiotemporal variability of precipitation across Pakistan using two temporal frameworks: 1951–2019 (long-term) and 1981–2019 (short-term). The results indicate substantial seasonal and regional variability in precipitation patterns, although most long-term trends remain statistically insignificant. Modest increases were observed in summer and autumn, while short-term analysis reveals more pronounced declines, particularly in spring and the cool season, alongside a notable increase in autumn precipitation.

Pettitt's test identified clear temporal shifts in precipitation regimes. Prior to 1981, significant changes were largely localized, mainly in Jammu and Kashmir (JK), Balochistan (BL), Khyber Pakhtunkhwa (KP), and Punjab (PJ). After 1981, these shifts became more spatially extensive, affecting both northern and southern regions, indicating a southward expansion and increasing variability in precipitation patterns.

Regionally, declining winter precipitation is evident in Gilgit-Baltistan (GB) and northwestern Balochistan, with reductions extending southward in the short-term period. In contrast, northern Punjab and KP exhibit relatively higher precipitation in the long-term, followed by a reduction in the short-term. Cool-season precipitation shows increasing trends in southern KP and parts of Sindh, while spring precipitation increases are more prominent in Balochistan, Sindh, and southeastern Punjab during the short-term period. Summer precipitation patterns remain strongly influenced by monsoon systems, with spatially heterogeneous trends across provinces.

These findings highlight an increasing instability in precipitation regimes across Pakistan, particularly after 1981, reflecting growing temporal variability and spatial redistribution of rainfall patterns.

Policy Implications

The observed shifts in precipitation patterns have important implications for water resource management and climate adaptation strategies in Pakistan. Declining cool-season precipitation may adversely affect irrigation planning, particularly in arid and semi-arid regions such as Sindh and Balochistan. Conversely, increased variability and intensity of summer precipitation elevate the risk of flooding, especially in monsoon-dominated regions. These findings emphasize the need for region-specific water management policies, improved flood risk governance, and adaptive agricultural practices to enhance resilience under changing precipitation regimes.

Limitations of the Study

This study relies on the GPCC gridded precipitation dataset at a 0.25° spatial resolution, which, although widely used, may introduce uncertainties in regions with sparse observational coverage, particularly in western Balochistan and Gilgit-Baltistan. Additionally, while the Modified Mann–Kendall test improves trend detection by accounting for autocorrelation, the analysis is limited to identifying the direction and statistical significance of trends without quantifying their magnitude. Therefore, the interpretation of results should be considered within these methodological and data constraints.

Future Recommendations

Future research should consider integrating higher-resolution or station-based datasets to improve reliability in data-scarce regions. The incorporation of magnitude-based trend estimators, such as Sen's slope, may further enhance the quantitative interpretation of precipitation changes. Additionally, linking precipitation variability with hydrological, agricultural, and socio-economic datasets would provide a more comprehensive understanding of climate impacts. The inclusion of climate model projections could also support long-term forecasting and policy planning for sustainable development.

Conflict of Interest

The author(s) declared no conflicts of interest for this article.

Author Contribution

Abdul Jameel Khan: Conceptualization (lead); writing–original draft (lead); data curation (lead); investigation (equal); visualization (supporting); formal analysis (supporting). Saqib-Ur-Rehmen: Conceptualization (supporting); supervision (lead). Kamran Khan: Conceptualization (equal); supervision (supporting), visualization (lead); investigation (equal); data curation (equal); formal analysis (equal). Atia Elahi: Investigation (supporting); data curation (supporting); writing–review and editing (supporting); resources (lead).

Data availability statement

Data sharing is not applicable to this study as no new data were created or analyzed in this article.

Acknowledgment

Not applicable

References

Adeel, M., Razzak, A., Riaz, S. M. F., & Iqbal, M. J. (2024). Impact of sea surface temperature in the Arabian Sea on the variability of Summer Monsoon Rainfall over Pakistan Region. *Dynamics of Atmospheres and Oceans*, *107*, 101482.

Ahmed, K., Shahid, S., & Nawaz, N. (2018). Impacts of climate variability and change on seasonal drought characteristics of Pakistan. *Atmospheric research*, *214*, 364-374.

Aksu, H., Cetin, M., Aksoy, H., Yaldiz, S. G., Yildirim, I., & Keklik, G. (2022). Spatial and temporal characterization of standard duration-maximum precipitation over Black Sea Region in Turkey. *Natural Hazards*, 1-27.

Ali, F.; Khan, N.; Ali, K.; Khan, M.E.H.; Jones, D.A. (2022). Vegetation Pattern and Regeneration Dynamics of the Progressively Declining *Monotheca buxifolia*. Forests in Pakistan: Implications for Conservation. *Sustainability*, *14*, 6111.

Arasa-Gisbert, R.; Vayreda, J.; Román-Cuesta, R.M.; Villela, S.A.; Mayorga, R.; Retana, J. (2018). Forest diversity plays a key role in determining the stand carbon stocks of Mexican forests. *For. Ecol. Manag*. *415*, 160–171.

Arshad, M. I., Iqbal, M. A., & Shahbaz, M. (2018). Pakistan tourism industry and challenges: a review. *Asia Pacific Journal of Tourism Research*, *23*(2), 121-132.

Asmat, U., & Athar, H. (2017). Run-based multi-model interannual variability assessment of precipitation and temperature over Pakistan using two IPCC AR4-based AOGCMs. *Theoretical and Applied Climatology*, *127*, 1-16.

Bhatta, L. D., Udas, E., Khan, B., Ajmal, A., Amir, R., & Ranabhat, S. (2020). Local knowledge based perceptions on climate change and its impacts in the Rakaposhi valley of Gilgit-Baltistan, Pakistan. *International Journal of Climate Change Strategies and Management*, *12*(2), 222-237.

Birsan, M. V., Molnar, P., Burlando, P., & Pfaundler, M. (2005). Streamflow trends in Switzerland. *Journal of Hydrology*, *314*(1-4), 312-329.

Blain, G. C. (2012). Revisiting the probabilistic definition of drought: strengths, limitations and an agrometeorological adaptation. *Bragantia*, *71*(1), 132-141.
De Jongh, I. L., Verhoest, N. E., & De Troch, F. P. (2006). Analysis of a 105-year time series of precipitation observed at Uccle, Belgium. *International Journal of Climatology*, *26*(14), 2023-2039.
De Oliveira-Júnior, J. F., Da Rosa Ferraz Jardim, A. M., Shah, M., De Gois, G., De Souza, A., Da Silva, M. V., Shahzad, R., Abbas, A., & Iqbal, M. S. (2022). Spatiotemporal analysis of drought and rainfall in Pakistan via Standardized Precipitation Index: homogeneous regions, trend, wavelet, and influence of El Niño-southern oscillation. *Theoretical and Applied Climatology*, *149*(1–2), 843–862. https://doi.org/10.1007/s00704-022-04082-9
Fahad, S., & Wang, J. (2018a). Farmers' risk perception, vulnerability, and adaptation to climate change in rural Pakistan. *Land Use Policy*, 79, 301–309
Fahad, S., & Wang, J. (2020). Climate change, vulnerability, and its impacts in rural Pakistan: a review. *Environmental Science and Pollution Research*, *27*(2), 1334-1338.
Fahad, S., Jing, W., Khan, A.A., Ullah, A., Ali, U., Hossain, M.S., Khan, S.U., Huong, N.T.L., Yang, X.Y., Hu, G.Y., & Bilal, A. (2018b). Evaluation of farmers' attitude and perception toward production risk: lessons from Khyber Pakhtunkhwa Province, Pakistan. *Hum Ecol Risk Assess Int J.*, *24*(6), 1710–1722
Gupta, A., Jain, M. K., Pandey, R. P., Gupta, V., & Saha, A. (2024). Evaluation of global precipitation products for meteorological drought assessment with respect to IMD station datasets over India. *Atmospheric Research*, 297, 107104.
Haleem, K., Ghanim, A. A. J., Khan, J., Khan, A. U., & Al-Areeq, A. M. (2023). Evaluating Future Streamflow Patterns under SSP245 Scenarios: Insights from CMIP6. *Sustainability*, *15*(22), 16117. https://doi.org/10.3390/su152216117
Hamed, K. H., & Rao, A. R. (1998). A modified Mann-Kendall trend test for autocorrelated data. Journal of hydrology, 204(1-4), 182-196. https://doi.org/10.1016/S0022-1694(97)00125-X
Hanif, M., Khan, A. H., & Adnan, S. (2013). Latitudinal precipitation characteristics and trends in Pakistan. *Journal of hydrology*, *492*, 266-272.
Hina, S., Saleem, F., Bibi, T., Hina, A., Mahmood, T., & Ullah, I. (2024). Exploring trends and variability of climate change indices in the agro-ecological zones of Pakistan and their driving mechanisms. *International Journal of Climatology*, *44*(10), 3589–3612. https://doi.org/10.1002/joc.8540
Hirsch, R. M., & Slack, J. R. (1984). A nonparametric trend test for seasonal data with serial dependence. *Water Resources Research*, *20*(6), 727-732.
Hussain, F., Nabi, G., & Wu, R.-S. (2021). Spatiotemporal Rainfall Distribution of Soan River Basin, Pothwar Region, Pakistan. *Advances in Meteorology*, *2021*, 1–24. https://doi.org/10.1155/2021/6656732
Iqbal, M. F., & Athar, H. (2018). Validation of satellite based precipitation over diverse topography of Pakistan. *Atmospheric Research*, *201*, 247-260.
Iqbal, Z., Shahid, S., Ahmed, K., Ismail, T., & Nawaz, N. (2019). Spatial distribution of the trends in precipitation and precipitation extremes in the sub-Himalayan region of Pakistan. *Theoretical and applied climatology*, *137*, 2755-2769.
Joshi, S., Jasra, W. A., Ismail, M., Shrestha, R. M., Yi, S. L., & Wu, N. (2013). Herders' perceptions of and responses to climate change in Northern Pakistan. *Environmental Management*, *52*, 639-648.
Kendall, M. G. (1955). Rank correlation methods.
Khan, F., Ali, S., Mayer, C., Ullah, H., & Muhammad, S. (2022). Climate change and spatio-temporal trend analysis of climate extremes in the homogeneous climatic zones of Pakistan during 1962-2019. *Plos One*, *17*(7), e0271626.

Latif, M., Syed, F. S., & Hannachi, A. (2017). Rainfall trends in the South Asian summer monsoon and its related large-scale dynamics with focus over Pakistan. *Climate Dynamics*, *48*(11), 3565-3581.

Lettenmaier, D. P., Wood, E. F., & Wallis, J. R. (1994). Hydro-climatological trends in the continental United States, 1948-88. *Journal of Climate*, *7*(4), 586-607.

Malik, I., Chuphal, D. S., Vegad, U., & Mishra, V. (2023). Was the extreme rainfall that caused the August 2022 flood in Pakistan predictable? *Environmental Research: Climate*, *2*(4), 041005. https://doi.org/10.1088/2752-5295/acfa1a

Mann, H. B. (1945). Nonparametric tests against trend. Econometrica 13: 245259Milly

Molnár, P., & Ramírez, J. A. (2001). Recent trends in precipitation and streamflow in the Rio Puerco Basin. *Journal of Climate*, *14*(10), 2317-2328.

Otto, F., Vautard, R., Zachariah, M., Yang, W., Kamil, S., Arulalan, T., Chaitra, S., Siddiqi, A., Mushtaq, H., Wolski, P., Pinto, I., Harrington, L., Barnes, C., Thalheimer, L., Aalst, M., Li, S., Arrighi, J., Kew, S., Philip, S., & Clarke, B. (2023). Climate change increased extreme monsoon rainfall, flooding highly vulnerable communities in Pakistan. *Environmental Research: Climate*, *2*(2), 025001. https://doi.org/10.1088/2752-5295/acbfd5

Pettitt, A.N. (1979). A non-parametric approach to the changepoint problem. *Appl Stat*, *28*, 126–135

Qureshi, H. U., Shah, S. M. H., & Teo, F. Y. (2023). Trend assessment of changing climate patterns over the major agro-climatic zones of Sindh and Punjab. *Frontiers in Water*, 5. https://doi.org/10.3389/frwa.2023.1194540

Raziei, T., Bordi, I., & Pereira, L. S. (2011). An application of GPCC and NCEP/NCAR datasets for drought variability analysis in Iran. *Water Resources Management*, *25*, 1075-1086.

Rehman, S. U., Khan, K., & Simmonds, I. (2019a). Links between Tasmanian precipitation variability and the Indian Ocean subtropical high. *Theoretical and Applied Climatology*, *138*, 1255-1267.

Rehman, S. U., Khan, K., Bilal A. U, Khan A. J., Hussain, S.A., & Zia, S. S. (2019c) An Analysis of Spatial and Temporal variation of Tasmanian Streamflow. *International Journal of Current Research*, *10*(2)(F), 31101-31104. (https://www.recentscientific.com/analysis-spatial-and-temporal-variations-tasmanian-streamflow) http://dx.doi.org/10.24327/ijrsr.2019.1002.3191

Rehman, S. U., Usmani, B. A., Khan, J., Khan, K., Zia, S. S., & Hussain, A. (2019b). A climatology of Indian Ocean Subtropical Anticyclone. *International Journal of Current Research*, *11*(3), 1913-1916. https://doi.org/10.24941/ijcr.34656.03.2019

Rudolf B, Schneider U (2005) Calculation of gridded precipitation data for the global land-surface using in-situ gauge observations. In: Proceedings of the 2nd workshop of the international precipitation working group IPWG, Monterey October 2004, EUMETSAT, ISBN 92-9110-070- 6, ISSN 1727-432X,

Safdar, F., Khokhar, M. F., Arshad, M., & Adil, I. H. (2019). Climate change indicators and spatiotemporal shift in monsoon patterns in Pakistan. *Advances in Meteorology*, *2019*(1), 8281201.

Safdar, F., Khokhar, M.F., Mahmood, F. et al. (2023). Observed and predicted precipitation variability across Pakistan with special focus on winter and pre-monsoon precipitation. *Environ Sci Pollut Res*. *30*, 4510–4530. https://doi.org/10.1007/s11356-022-22502-1,pp 231–247.

Schneider U, Fuchs T, Meyer-Christoffer A, Rudolf B (2008) Global precipitation analysis products of the GPCC. Global Precipitation Climatology Centre (GPCC), DWD, Internet Publication (http://www.dwd.de), pp 1–12

Schneider, U., Finger, P., Meyer-Christoffer, A., Rustemeier, E., Ziese, M., & Becker, A. (2017). Evaluating the hydrological cycle over land using the newly-corrected precipitation climatology from the Global Precipitation Climatology Centre (GPCC). *Atmosphere*, *8*(3), 52.

Waseem, M., Ahmad, I., Mujtaba, A., Tayyab, M., Si, C., Lü, H., & Dong, X. (2020). Spatiotemporal Dynamics of Precipitation in Southwest Arid-Agriculture Zones of Pakistan. *Sustainability*, *12*(6), 2305.

Xu, J., & Grumbine, R. E. (2014). Building ecosystem resilience for climate change adaptation in the Asian highlands. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(6), 709-718.

Yonus, M., Jan, B., Khan, H., Nawaz, F., & Ali, M. (2023). Study the seasonal trend analysis and probability distribution functions of rainfall for atmospheric region of Pakistan. *MethodsX*, *10*, 102058.

Zaman, M., Shen, Y., Shahid, M. A., Khan, M. I., Saifullah, M., Usman, M., & Ahmad, I. (2023). Spatiotemporal variability of precipitation concentration in Pakistan. *International Journal of Climatology*, *43*(16), 7646–7666. https://doi.org/10.1002/joc.8285