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RESEARCH

Evolving climatic patterns and drought risk in Pakistan's agro-ecological zones

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Abstract

Climate change is altering global weather systems, posing climatic challenges for Pakistan through shifting precipitation patterns and rising temperatures. This study examines spatiotemporal variations in climate change and drought patterns across Pakistan's Agro-Ecological Zones (AEZs) from 1991 to 2023. Using ECMWF atmospheric reanalysis of the global climate (ERA-5) reanalysis data, we analyze precipitation and air temperature anomalies for 2023 to assess climate variability in all AEZs. To capture the spatial trend and severity of drought, we utilize the Precipitation Condition Index (PCI) and Air Temperature Condition Index (ATCI). Additionally, the Standardized Precipitation Index (SPI) is applied to evaluate long-term drought trends. Drought intensity has escalated, particularly in Punjab's agricultural heartlands, AEZ of Northern irrigated plain, threatening crop productivity and food security. From 1991 to 2020, droughts were concentrated in Sindh and Baluchistan's Dry Plateau, Coastal Zone, and Southern Irrigated Plains. By 2021–2023, droughts expanded from North of Sindh to South of Punjab and Northern irrigated plains. Precipitation deficits were observed in February (46.34 mm to 25.6 mm, a 44.7% drop) and August (81.66 mm to 29.78 mm, a 63.5% decline), related to critical stages of crop development, marking some of the driest conditions recorded since 1991. Conversely, temperature anomalies revealed marked warming trends, with February temperatures rising from 8.11 °C to 10.8 °C (+2.7 °C) and March from 13 °C to 13.5 °C (+0.5 °C). September saw a rise from 22.6 °C to 23.9 °C (+1.3 °C), while increases were noted in October (17.9 °C to 18.4 °C), November (12 °C to 13 °C), and December (7.21 °C to 8.5 °C). This study also found that nearly all AEZs experienced drought in 2000–2005, 2010, 2018 and 2022. While all AEZs showed positive wet trend after 2022, except TM, RP and NDM AEZs are in dryness from 2018 and still continued after 2022. The 2022 floods, compounded by erratic droughts, devastated major crops like wheat, cotton, barley, and rice, exacerbating food insecurity. These findings underscore the urgent need for adaptive measures tailored to regional climatic conditions. Implementing high-precision climate monitoring systems and region-specific drought management strategies are essential to mitigating climate change's adverse effects on Pakistan's agricultural sustainability and environmental stability.

Keywords Adaptation · Agro-ecological zones (AEZs) · Climate change · Droughts · Floods · Food security · Pakistan · Precipitation anomalies · Temperature variability · SPI · ATCI, PCI

1 Introduction

Global warming and sudden shifts between wet and dry periods are consequences of climate change that are severely impacting human and natural systems. By the end of the 21st century, the frequency of these events is projected to increase by 2.56 ± 0.16 times compared to 1979–2019 levels, with more rapid and intense transitions. The most significant changes in precipitation patterns are expected in monsoon and polar regions (Tan et al. 2023). Global surface temperature has risen by about ≈ 0.2 °C per decade over the past 30 years (Lindsey and Dahlman 2024).

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In Pakistan, precipitation trends increased from 1995 to 2013 compared to 1976–1994, both annually and during the monsoon season (Iqbal and Athar 2018). Annual precipitation in arid regions has risen significantly by 0.828 mm yr^{-1}. At the same time, maximum temperatures have increased by 0.014 °C yr^{-1} in extremely arid regions and by 0.018 °C yr^{-1} in humid regions. Minimum temperatures have also shown an upward trend in Pakistan (Adnan et al. 2017a). Pakistan is ranked first among countries most affected by climate change (Adil et al. 2025). These slow-onset changes have been linked to the intensification of extreme weather events. Due to precipitation change, unprecedented monsoon rains and subsequent floods, especially in 2022, which affected over 33 million people, were intensified by climate change (Qamer et al. 2023) have further threatened the nation's agricultural productivity, food security, and water management (Syed et al. 2022). Since 1950, the country has faced 28 major riverine floods, including the catastrophic 2010 floods and the unprecedented monsoon floods of 2022 (Waseem et al. 2023). These floods have become more frequent, exacerbated by erratic weather patterns, with rain-fed agriculture—on which 60% of the population depends—being highly vulnerable (Chaudhry 2017).

Concurrently, Pakistan has faced major droughts, particularly in regions Sindh and southern Punjab, which have suffered from severe dry spells in 1871, 1899, 1942, and more recently in 1999–2002 and 2020–2022 (PDMA 2023). These droughts have led to critical water shortages, declining groundwater levels, and worsening food insecurity. The 1999 drought alone affected 1.4 million people, 5.6 million livestock, and over 12 million acres of agricultural land. Recent La Niña events between 2020 and 2021 brought 77% less rainfall to drought-prone areas, exacerbating food insecurity for an estimated 1.8 million people (PDMA 2023). In Punjab, there were severe drought events in 2000–2003, 2006–2008, 2013, 2017, and 2018 (Rahman et al. 2023a). These extreme precipitation and temperature anomalies—flooding and drought—underscore the urgent need for adaptive strategies to cope with Pakistan's increasing climate variability and its impact on water availability, agriculture, and human life.

Agro-ecological zones (AEZs) in Pakistan represent distinct geographical areas characterized by unique climate, soil, topography, and vegetation, which determine the most suitable agricultural practices for each region. These zones are defined to optimize land use and crop production, ensuring sustainable agriculture based on the natural characteristics and potential of each area. Drought conditions persisted across all AEZs, with significant warming observed in the southern, central, and southwestern zones. Drought has severe physical, economic, and environmental consequences, including declining groundwater levels and the depletion of wells, lakes, and springs (Sadiq and Saboor 2023). Additionally, precipitation levels dropped in the southern, northern, central, and southwestern regions, exacerbating the challenges faced by these areas (Dilawar et al. 2021). Extreme temperature and precipitation events are becoming more frequent, prolonged, and intense, and their effects on crop yields can vary—either positively or negatively—depending on the local climate conditions (Villa-Falfán et al. 2023). Temperature and precipitation variations increase crop production risks in Pakistan's vast agricultural region, particularly in the Southern Punjab (Amin et al. 2018).

As highlighted in recent studies, remote sensing-based indices for drought monitoring can generally be classified into four main categories (Abbas et al. 2014): spectral indices (e.g., Normalized Multiband Drought Index (NMDI) (Wang and Qu 2009), Normalized Difference Drought Index (NDDI) (Salas-Martínez et al. 2023); condition-based indices (e.g., Temperature Condition Index (TCI) (Kogan, 1995), Vegetation Condition Index (VCI) (Kogan, 1995), Precipitation Condition Index (PCI); surface temperature and crop water stress indices (e.g., Crop Water Stress Index (CWSI) (Jackson et al. 1981), Evaporative Stress Index (ESI) (Anderson et al. 2011), Vegetation Health Index (VHI), Temperature-Vegetation Drought Index (TVDI) (Sandholt et al. 2002); and classical climatic (e.g., Standardized Precipitation Index (SPI) (McKee et al. 1993), Palmer Drought Severity Index (PDSI) (Palmer 1965) or integrated multi-sensor indices (e.g., Microwave Integrated Drought Index (MIDI) (Zhang and Jia 2013), Synthesized Drought Index (SDI) (Du et al. 2013). While several studies have examined drought and flood vulnerability in Pakistan, most are limited by short timeframes or localized focus, lacking a comprehensive zone-wise perspective. Few have systematically analyzed the spatiotemporal dynamics of temperature, precipitation, and drought across all AEZs over extended periods, and detailed multi-scale assessments using condition-based indices remain scarce.

In this study, we used monthly air temperature and total precipitation data derived from the ERA5-Land reanalysis dataset developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5-Land offers high spatiotemporal consistency, strong correlations with ground-based observations, and proven reliability in capturing seasonal climate variability, making it well-suited for hydrometeorological analysis (Izadi et al. 2021). Over Pakistan, ERA5 data aligns closely with station records and effectively represents both seasonal patterns and regional climate anomalies (Izadi et al. 2021; Latif et al. 2024a). The main objectives of the study included: (1) to assess changes in air temperature and precipitation anomalies across all AEZs of Pakistan from 1991 to 2023, (2) to investigate historical drought trends using the Standardized Precipitation Index (SPI) at 3-, 6-, 9-, and 12-month timescales (McKee et al. 1993), and (3) to monitor the spatiotemporal dynamics of drought using condition-based indices—namely, the Air Temperature Condition Index (ATCI), based on the TCI) (Kogan 1995; and the PCI (Lingtong et al. 2013). These condition-based indices provide a quick overview of underlying conditions and help to quantify the impacts of climate stressors by providing a more detailed understanding of the drought-climate nexus (Zhang et al. 2017).

1.1 Geographic settings and agro-ecological zones (AEZs) of Pakistan

Pakistan, located in South Asia at the crossroads of the Middle East and Central Asia, spans from 24° to 37° N latitude and 60° to 77° E longitude (Figure 1a). Its diverse terrain includes the high-altitude Himalayas in the north—home to K2 (8,611 m), the world's second-highest peak (also known as Chhogori, Qogir, Ketu, or Mount Godwin-Austen)—along with expansive river plains and arid deserts in the south. The country's climate, as varied as its topography, ranges from dry and hot along the coastal areas and the Indus River lowlands to cooler conditions in the northern uplands and Himalayas. Pakistan's climatic zones include a continental climate in the north (Gilgit-Baltistan, Kashmir, and KPK), a mountainous dry climate in the west (Baluchistan), a wet climate in the east (Punjab), an arid climate in the Thar Desert, and a tropical climate in the southeast (Sindh). This geographic positioning and topographic diversity lead to significant seasonal and daily temperature variations.

Pakistan's agriculture plays a critical role in the national economy, contributing 24% to GDP, employing nearly half of the labour force, and serving as a major source of foreign exchange (PBS 2020). The country's diverse landscape and climate have led to the classification of 11 Argo-Ecological Zones (AEZs) by the Food and Agriculture Organization (FAO) (FAO 2024), each with distinct agricultural and environmental characteristics (Figure 1b). These AEZs include Coastal Zone (SZ), Dry Plateau (DP), Jammu & Kashmir (JK), Northern Dry Mountain (NDM), Northern Irrigated Plains (NIP), Piedmont Plain (PP), Rainfed Plateau (RP), Sandy Desert (SD), Southern Irrigated Plain (SIP), Temperate Mountain (TM), and Western Dry Mountain (WDM). Pakistan's climate varies significantly, with the northern highlands experiencing cold, snowy conditions and the southern plains enduring extreme heat, where temperatures can reach up to 53 °C (127 °F) in June (WMO 2019).

2 Materials and methods

This study utilized multiple datasets to assess air temperature and precipitation anomalies, along with drought dynamics, across AEZs from 1991 to 2023 (Fig. 2 presents the overall methodological framework used in the study).

2.1 Description of data used

The primary climatic data source was the ERA5-Land dataset, developed by the ECMWF. With a spatial resolution of approximately 11 km, this provides consistent and long-term climate variables. Key variables such as total monthly precipitation sum and air temperature were accessed from the ERA5-Land Monthly Aggregated Dataset ("ECMWF/ERA5_LAND/MONTHLY_AGGR") through Google Earth Engine (GEE). ERA5 gridded data were spatially clipped to each AEZ boundary using the clip function in GEE, and the mean function was applied to compute average pixel values within each zone. This process was performed independently for each AEZ and time interval, assuming equal weighting for all pixels without additional area-based adjustments. The robustness of ERA5's spatial and temporal coverage, combined with its low root mean square error and strong correlation values (e.g., $R \approx 0.81$ at daily scale), ensures reliable analysis across diverse zones and timeframes. Collectively, this approach offers valuable insights into evolving drought risks and climate variability

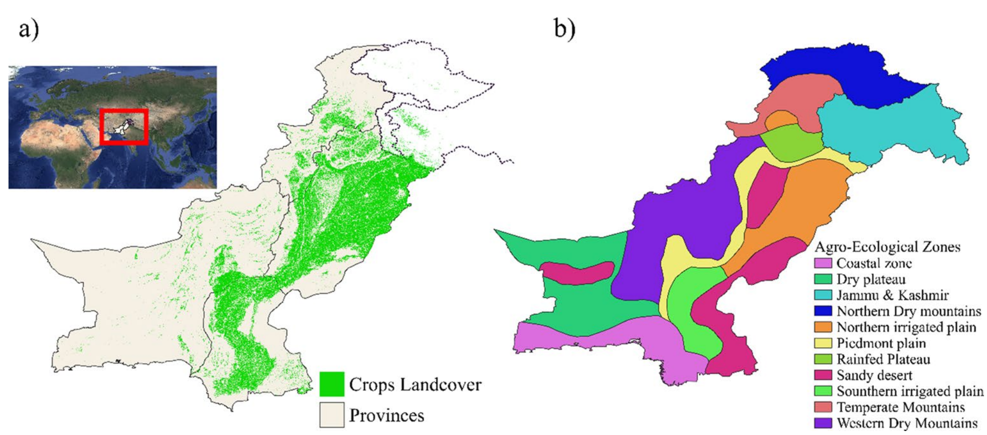

Fig. 1 (**a**) Geographical Location of Pakistan and Crop-land cover in Pakistan by (ESA) (**b**) Agro–Ecological Zones of Pakistan (FAO 2024)

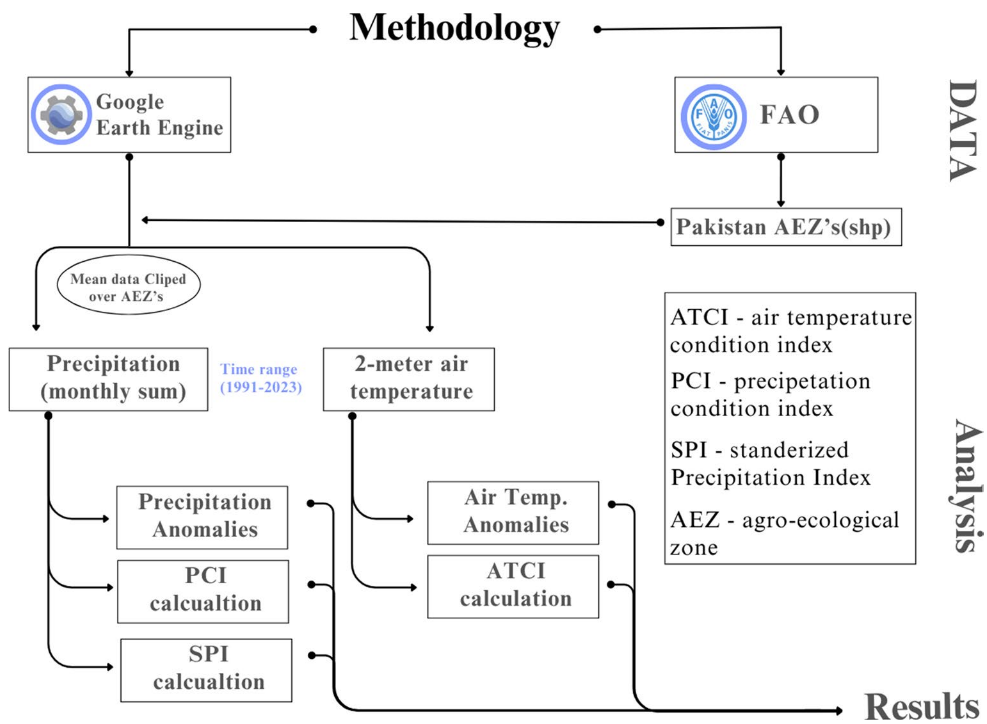

Fig. 2 Methodology flow chart of this study

across Pakistan's agricultural regions (Arshad et al. 2021). Additional datasets included the ESA WorldCover 2021 land cover classification at 10-meter resolution (Zanaga et al. 2021), used to identify cropland cover, and the FAO-provided shapefile of Pakistan's 11 AEZs (FAO 2024), which was used to geographically subset the analysis.

2.2 Anomalies and indices

Air-temperature and precipitation anomalies were calculated relative to the 30-year climate normal period (1991–2020) as base years, by climatological standards (Livezey et al. 2007) to detect emerging trends and recent anomalies with the recent data of 2023. To evaluate drought conditions, three major indices were applied. The PCI (Lingtong et al. 2013), was used to assess drought conditions due to precipitation change, while the ATCI, adapted from the TCI (Kogan 1995) was employed to analyze air-temperature-related stress. The PCI and ATCI temporal analysis further divided the full study period into seven intervals: 1991–1995, 1996–2000, 2001–2005, 2006–2010, 2011–2015, 2016–2020, and 2021–2023. Additionally, the SPI (McKee et al. 1993), was calculated at multiple timescales (3, 6, 9, and 12 months) to capture both short- and long-term drought patterns. While shorter SPI timescales, 3- to 6-months, are typically used to assess agricultural droughts, whereas longer timescales are better suited for evaluating water resource impacts such as reservoir storage, streamflow, and groundwater levels (Zhang et al. 2023). These indices together provided a comprehensive view of climatic variability and potential drought impacts.

2.3 Precipitation and temperature anomalies

Precipitation and temperature anomalies, representing deviations from the long-term average (1991–2020), were calculated using Eq. 1 (Bell 2024).

$$\text{Anomaly} = X - X' \tag{1}$$

Where X is the observed value, and X' is the long-term average for the variable. This approach allows for the identification of significant patterns, such as warming trends, droughts, or shifts in precipitation. For temperature anomalies, positive values indicate temperatures above the long-term average, while negative values indicate below-average temperatures. Similarly, for precipitation anomalies, positive values indicate wetter-than-average conditions, whereas negative values indicate drier-than-average conditions. Precipitation and air-temperature anomalies, representing simple arithmetic deviations from the long-term average, were calculated using Eq. 1.

2.4 Precipitation condition index (PCI)

The PCI, as defined in Eq. 2, is an important indicator for water resource planning, drought and flood risk prediction, and natural resource management (Zhang et al. 2019). PCI is a remote sensing-based index that take precipitation data and ranges mentioned in table-1 (Lingtong et al. 2013).

$$PCI = \frac{(Prec_{avg} - Prec_{min})}{(Prec_{max} - Prec_{min})} \times 100 \quad (2)$$

The variables $Prec_{avg}$, $Prec_{min}$ and $Prec_{max}$ represent the average, minimum, and maximum precipitation.

2.5 Air-Temperature conditions index (ATCI)

We adopted the ATCI, with its ranges provided in Table 1, based on the TCI, which uses land surface temperature (Kogan 1995), Eq. 3. ATCI is used to evaluate variations in air-temperature conditions, calculated based on the maximum and minimum air-temperatures, evaluates plants stress. However, in this study, we used the mean air temperature instead of LST by maintaining the same 0 to 100 scale.

$$ATCI = \frac{(Temp_{avg} - Temp_{max})}{(Temp_{max} - Temp_{min})} \times 100 \quad (3)$$

The variables $Temp_{avg}$, $Temp_{min}$ and $Temp_{max}$ represent the average, minimum, and maximum air-temperature.

The PCI and ATCI was calculated for each five-year period across the different AEZs to analyze the spatial and temporal variations in precipitation condition patterns over the past 33 years. We applied fiveyear bin of moving averages to filter out shortterm atmospheric variability—which complicates interannual to decadal forecasts (Smith et al. 2019)—while retaining the underlying longerterm trends, cyclical patterns, and sporadic fluctuations in the precipitation series (Wang et al. 2018). The PCI and ATCI provide valuable information on environmental conditions by categorizing moisture and temperature stress into different severity levels as shown in table-1 (UNU 2024 b).

Table 1 Condition classification categories for PCI, ATCI and SPI indices

PCI/ATCI		SPI	
Range	Condition Classification	Range	Condition Classification
0–10	Extreme dry conditions		
10–20	Severe dry conditions		
20–30	Moderate dry conditions	≥2.00	Extremely wet
30–40	Mild dry conditions	1.50 to 1.99	Very wet
40–60	Normal conditions	1.00 to 1.49	Moderately wet
60–70	Mild wet conditions	−0.99 to 0.99	Near normal
70–80	Moderate wet conditions	−1.00 to −1.49	Moderate drought
80–90	Severe wet conditions	−1.50 to −1.99	Severe drought
90–100	Extreme wet conditions	≤ −2.00	Extreme drought

2.6 Standardized precipitation index (SPI)

The World Meteorological Organization recognizes the SPI, Eq. 4, as an effective tool for monitoring and tracking meteorological drought conditions (Hayes et al. 2011). The SPI is the main meteorological drought index that the WMO advises nations to use while tracking and studying drought conditions (Bera et al. 2021).

SPI (McKee et al. 1993) provides a standardized measure of precipitation deficits or surpluses over various time frames, allowing for consistent assessment and comparison of drought conditions across different locations and periods. The SPI is flexible in terms of both space and time, and it is quite sensitive to drought (Li et al. 2024). SPI values range from −3 to +3, with further classifications shown in Table 1 (McKee et al. 1993) (Vicario et al. 2019). The flexibility of SPI to be calculated over different periods (e.g., 1 month, 6 months, 12 months) makes it versatile for assessing drought impacts on various sectors, such as agriculture and hydrology (Adnan et al. 2015a). For robust analysis, it is recommended to use at least 30 years of precipitation data (Guttman 1999).

$$SPI = \frac{(P - P^*)}{\sigma_P} \quad (4)$$

Where, P is observed precipitation, P^* is mean precipitation, and σ_P is standard deviation of precipitation. We employed the SPI at four-time scales (3, 6, 9 and 12 months) to analyze historical and spatial drought trends across the AEZs of Pakistan. These indices helped to assess drought severity, duration, and distribution in different Agro-ecological zones. These four SPI timescales were selected to capture both short-term droughts relevant to agriculture (e.g., 3- and 6-month) and long-term droughts that affect water resources and hydrological systems (e.g., 9- and 12-month) (Adnan et al. 2015b; Li et al. 2024).

3 Results

The spatiotemporal analysis of precipitation and temperature anomalies from 1991 to 2023 revealed climatic variability across the AEZs. In 2023, monthly precipitation anomalies showed sharp negative deviations in February, August and December, marking the lowest precipitation levels recorded since 1991 in Pakistan, especially in AEZs of Temperate and NDM, RP, NIP and the western region of JK. Conversely, positive anomalies were observed in May and July, with particularly high precipitation levels recorded in the JK region. Temperature anomaly analysis indicated warming trends in February, August, September, November

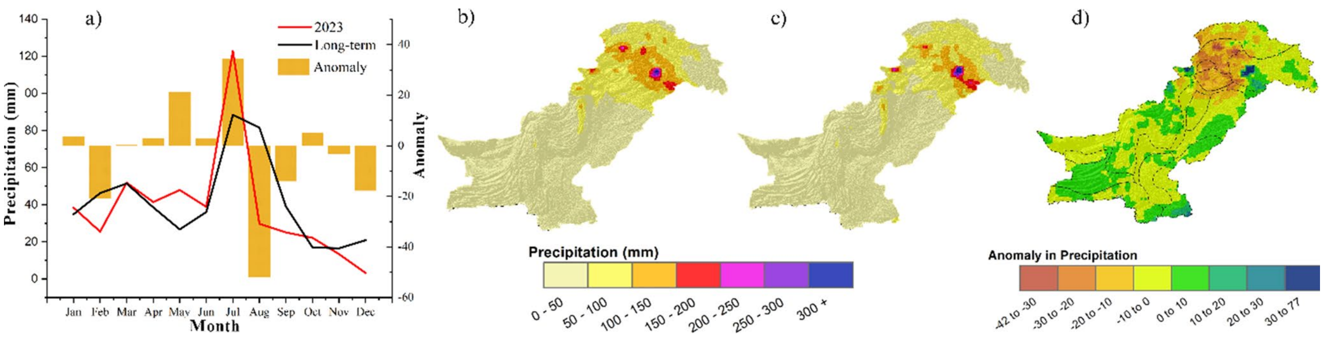

Fig. 3 Spatial and temporal patterns of precipitation across Pakistan: (**a**) Graphical representation of monthly means precipitation for 1991–2020, 2023, and the anomalies; (**b**) Long-term mean precipitation (1991–2020); (**c**) Annual mean precipitation in Pakistan for 2023; (**d**) Spatial distribution of anomalies in precipitation variation across Pakistan for 2023

Table 2 Pakistan's historic monthly mean and 2023 precipitation values and anomaly values in these months classified into categories

Month	Historic (mm)	2023 (mm)	Anomaly (mm)	Category	Precipitation Anomalies Classification (fig 3d)	
January	34.92	38.51	+3.59	Slightly wet		
February	46.70	25.60	−21.10	Severe dry		
March	51.50	51.94	+0.44	Slightly wet	Range	Class
April	38.64	41.52	+2.88	Slightly wet		
May	26.70	48.00	+21.30	Severe wet	≤ −30	Extreme dry/deficit
June	36.16	38.92	+2.76	Slightly wet	−30 to −20	Severe dry/deficit
July	88.51	123.00	+34.49	Extreme wet	−20 to −10	Moderate dry/deficit
August	81.70	29.80	−51.90	Extreme dry	−10 to 0	Slightly dry/deficit
September	39.12	25.20	−13.92	Moderate dry	0 to 10	Slightly wet/surplus
October	17.02	22.22	+5.20	Slightly wet	10 to 20	Moderate wet/surplus
November	16.60	13.40	−3.20	Slightly dry	20 to 30	Severe wet/surplus
December	20.90	3.30	−17.60	Moderate dry	30 +	Extreme wet/surplus

and December in 2023, while cooler-than-average conditions were observed in January, April and May. Zones such as the western SD, DP, RP, TM and eastern region of JK exhibited high positive temperature anomalies, reflecting elevated thermal stress. Furthermore, SPI analysis at multiple timescales (3, 6, 9, and 12 months) identified periods of increased drought frequency, particularly during 1999–2005 across all AEZ's and in 2018–2022. These temporal patterns highlight the intensity and variability of hydroclimatic extremes within and between AEZs during the study period.

3.1 Precipitation anomalies

Noticeable changes in precipitation were observed throughout 2023. Various aspects of precipitation patterns in Pakistan were evaluated by comparing the long-term monthly precipitation means (1991–2020) with 2023 and highlighting the resulting anomalies (Fig. 3). Specifically, Fig. 3a shows a graphical comparison of the long-term monthly precipitation means and the 2023 values, along with the corresponding anomalies, while Fig. 3b depicts the spatial distribution of long-term mean precipitation from 1991 to 2020. Figure 3c presents the annual mean precipitation for 2023, and Fig. 3d illustrates these anomalies in precipitation spatially across Pakistan for 2023. The thresholds for classifying anomaly categories (e.g., extreme dry, moderate wet), as shown in Tables 2 and 3, are not fixed; instead, they were defined based on the observed values to allow improved visual interpretation, and we ensured equal distances between the ranges. Table 2 provides the historic mean and 2023 monthly precipitation values, with the corresponding anomalies classified from extreme wet, indicating surplus precipitation, to extreme dry, indicating a deficit.

As shown in Fig. 3a, we observed an extreme precipitation deficit in August and a severe deficit in February across Pakistan, along with extreme wet conditions in July 2023. The TM AEZ showed an extreme dry condition, highlighting a significant decline in precipitation, while the northern NIP, western JK, and the RP exhibited severe dryness, indicating substantial deficits. Conversely, the Jammu and Kashmir AEZ displayed an extreme surplus, pointing to significant increases in precipitation, which likely contributed to the 2023 floods.

3.2 Air temperature anomalies

Air temperature anomalies indicate deviations from the historical average, providing insight into climatic shifts

Table 3 Pakistan's historic monthly mean and 2023 air temperature values and anomalies values in these months classified into categories

Month	Historic (°C)	2023 (°C)	Anomaly (°C)	Category	Air Temperature Anomalies Classification (fig 3d)	
January	5.23	3.86	−1.37	Moderate Cold		
February	8.11	10.78	+2.67	Extreme Warmth		
March	12.99	13.50	+0.51	Moderate Warmth	Range	Class
April	18.45	17.27	−1.18	Extreme cold		
May	23.13	21.39	−1.74	Extreme cold	≤ −0.80	Extreme cold
June	25.71	25.18	−0.53	Severe Cold	−0.80 to −0.50	Severe cold
July	25.83	25.37	−0.47	Moderate Cold	−0.50 to −0.20	Moderate cold
August	24.83	25.61	+0.78	Moderate Warmth	−0.20 to 0	Slight cold
September	22.59	23.85	+1.26	Strong Warmth	0 to +0.50	Slight warmth
October	17.86	18.36	+0.51	Moderate Warmth	0.50 to +1	Moderate warmth
November	11.95	12.97	+1.01	Severe Warmth	+1 to +1.50	Severe warmth
December	7.21	8.50	+1.29	Severe Warmth	1.50 +	Extreme warmth

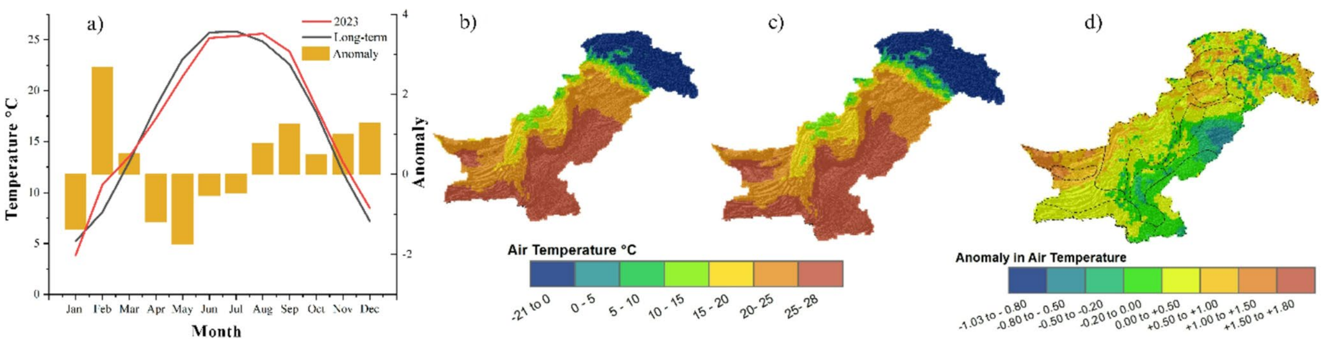

Fig. 4 Spatial and temporal patterns of air temperature across Pakistan: (**a**) Graphical representation of monthly means air temperature for 1991–2020, 2023, and the anomalies; (**b**) Long-term mean air temperature (1991–2022); (**c**) Annual mean air temperature in Pakistan for 2023; (**d**) Spatial distribution of anomalies in air temperature variation across Pakistan for 2023

(Fig. 4). Figure 4a shows a graphical comparison of the long-term monthly air temperature means and the 2023 values, along with the corresponding anomalies, while Fig. 4b depicts spatial patterns of the long-term mean air temperature from 1991 to 2020. Figure 4c presents the annual mean air temperature for 2023, and Fig. 4d illustrates these anomalies in air temperature spatially across Pakistan for 2023.

As shown in Fig. 4a, we observed extreme warmth in February and severe warmth in November and December across Pakistan, along with a cold trend from April to July in 2023. Several AEZs experienced significant warming, including the western SD and DP in Baluchistan, TM, NIP, RP, northeast JK, and WDM, reaching severe to extreme warmth levels. AEZ's of PP, northern DP and north region of NIP, CZ and WDM also experienced slight warming. These deviations highlight substantial air temperature shifts across Pakistan, with many regions showing signs of increased temperature stress and potential drought conditions.

3.3 PCI and ATCI results

The analysis of PCI and ATCI across Pakistan's Agro-Ecological Zones (AEZs) from 1991 to 2023—considering seven bin of periods (1991–1995, 1996–2000, 2001–2005, 2006–2010, 2011–2015, 2016–2020, and 2021–2023)—reveals spatial and temporal variability in precipitation and air temperature condition patterns (Fig. 5). Over this period, drought conditions progressively worsened, particularly in the AEZ's of CA, SD and SIP. During 1991–1995, extreme drought was evident in these regions, with PCI values ranging from 13 to 20 (Fig. 5a). The Northern Dry Mountain and JK AEZ's, on the other hand, experienced wetter conditions, with PCI values above 50, indicating an absence of drought. Between 1996 and 2000 (Fig. 5b), drought conditions expanded, extending from SD zone toward the NIP zone. From 2001 to 2020 (Figs. 5c-f), the drought footprint deepened, spreading to the AEZ's of CP, DP, PP, and SD, which significantly impacted water resources and agriculture. In the most recent period (2021–2023, Fig. 5e), the Sandy Zone continued to experience extreme drought, while the Coastal Zone and Southern Irrigated Zone also saw severe drought conditions. The Western Dry Mountain region exhibited slight drought challenges, and a significant portion of the NIP Zone—vital for agricultural production—showed signs of increasing dryness, exacerbating water scarcity and crop yield concerns.

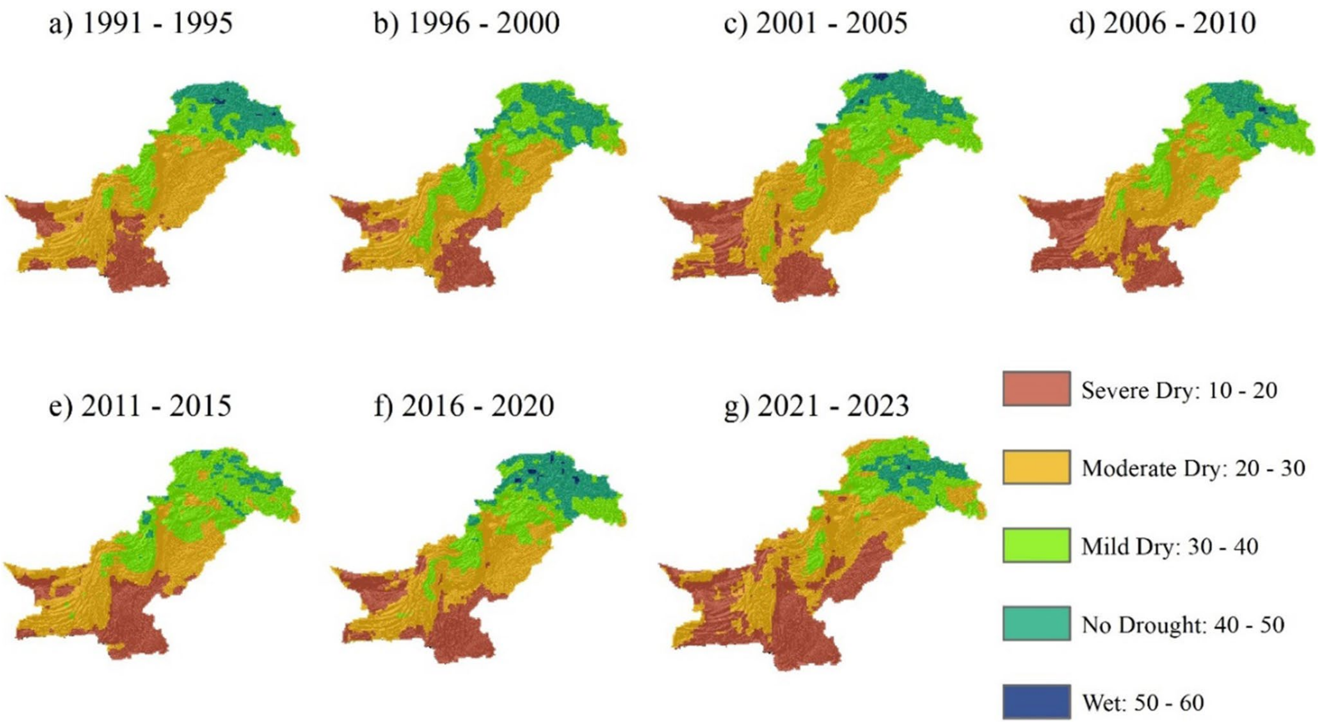

Fig. 5 Precipitation conditions across Pakistan for seven periods: (**a**) 1991–1995, (**b**) 1996–2000, (**c**) 2001–2005, (**d**) 2006–2010, (**e**) 2011–2015, (**f**) 2016–2020, and (**g**) 2021–2023

The ATCI also highlights that the impacts of climate variations have evolved over time (Fig. 6). Between 1991 and 2020, temperature stress conditions were primarily confined to the DP, Coastal Zone, SIP, and Sandy Desert AEZs (Figs. 6a-f). However, a notable shift has occurred in recent years, particularly from 2021 to 2023, where these adverse conditions have started affecting the NIP Zones, Western Dry Mountain, and Piedmont regions—areas that previously exhibited resilience to such climatic stress. This expansion of drought-prone areas (Figs. 5 and 6) into critical agricultural zones, such as the Northern Irrigated Plains of Punjab, reinforces the growing vulnerability of Pakistan's agricultural sector to changing climatic conditions.

3.4 SPI analysis (3-month scale)

The analysis of flash drought patterns from 1991 to 2023 reveals significant drought variability across the AEZs, captured using the 3-month SPI (Fig. 7). The CZ observed severe droughts in 2000–2005, 2018, and 2021, while the DP experienced a prolonged dry spell from 2000 to 2005, with another droughts period are 1992, 2004, 2018 and 2021. The TM also faced multiple severe droughts, notably in 1997, 1999–2005, 2010–2011, 2018, and 2022. PP experience extreme drought from 1999 to 2005 and most recently in 2022. The N & SIP experienced frequent droughts, affecting agriculture and water availability, particularly in 1999–2005, 2010, 2017–2019 and 2022. The SD and WDM had extended droughts from 1999 to 2005 and in 1992, with extreme events in 2001 and most recent in 2022. The Rainfed Plateau also experienced dry conditions in 2000–2001 and 2011, with the most recent prolonged period occurring and continue from 2021 to 2023. At the national level, Pakistan there were flash drought transitions in 1999–2005, 2011, 2018, 2001–2022.

3.5 SPI based drought analysis at the six-monthly scale across the AEZs

The six-month SPI analysis showed significant medium-term drought impacts across the AEZs, highlighting prolonged dry spells that have severely affected agriculture (Fig. 8). From 1999 to 2005, all AEZs experienced prolonged drought, leading to major challenges in crop growth, irrigation, and pasture conditions. In the CZ, extreme dryness was noted in 1992, 2002, and 2003 with more recent severe dry periods from 2018. The DP suffered severe dryness in 2000 and 2002 with more recent severe dry condition in 2018, while JK experienced extreme droughts in 2003 & 2018 and severe dry condition in 2022. The PP experienced extreme dry conditions in 2001, with the most recent period persisting from 2021 to 2023. The NIP faced severe drought between 2001 and 2005, with further extreme conditions in 2012, 2017–2019, and 2022. Similarly, the WDM endured

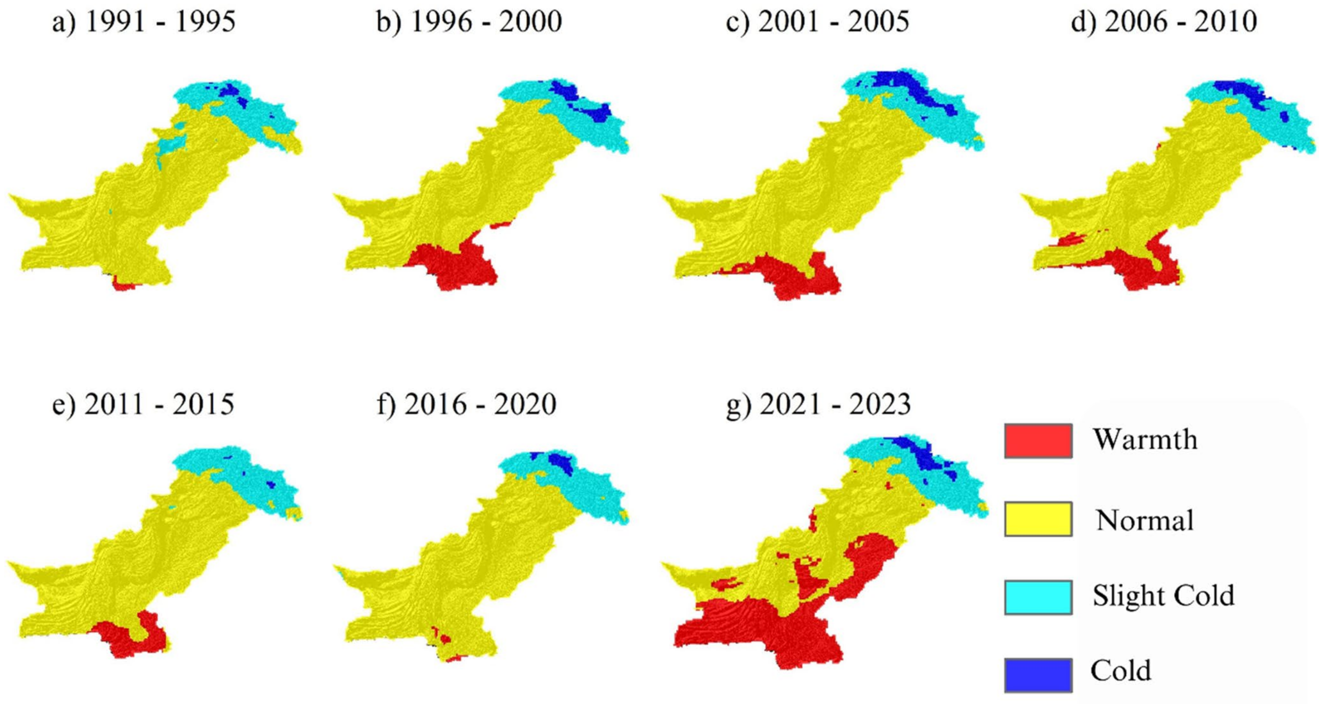

Fig. 6 Temperature conditions across Pakistan for seven periods: (**a**) 1991–1995, (**b**) 1996–2000, (**c**) 2001–2005, (**d**) 2006–2010, (**e**) 2011–2015, (**f**) 2016–2020, and (**g**) 2021–2023

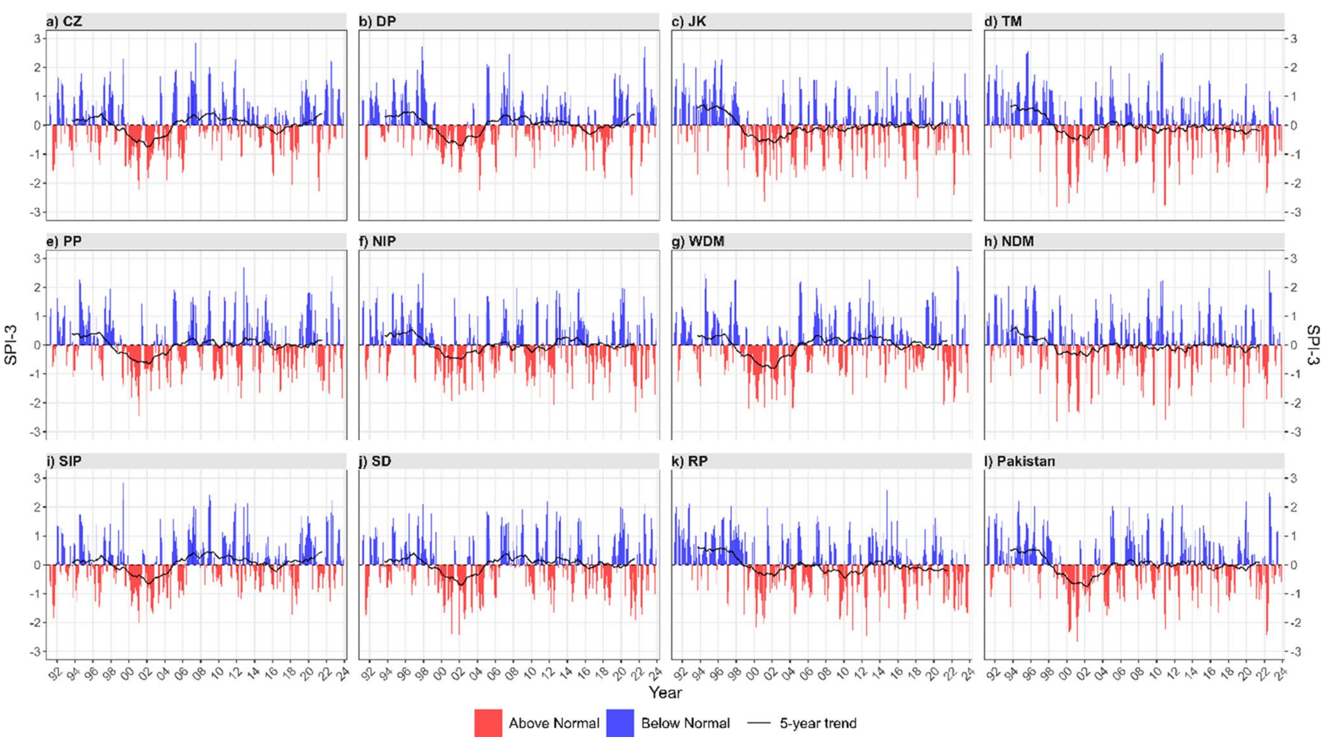

Fig. 7 3-month-scale SPI-based drought analysis across Pakistan's AEZs: (**a**) Coastal Zone, (**b**) Dry Plateau, (**c**) Jammu & Kashmir, (**d**) Temperate Mountains, (**e**) Piedmont Plain, (**f**) Northern Irrigated Plains, (**g**) Western Dry Mountains, (**h**) Northern Dry Mountains, (**i**) Southern Irrigated Plain, (**j**) Sandy Desert, (**k**) Rainfed Plateau, (**l**) Over-all Overview of Pakistan

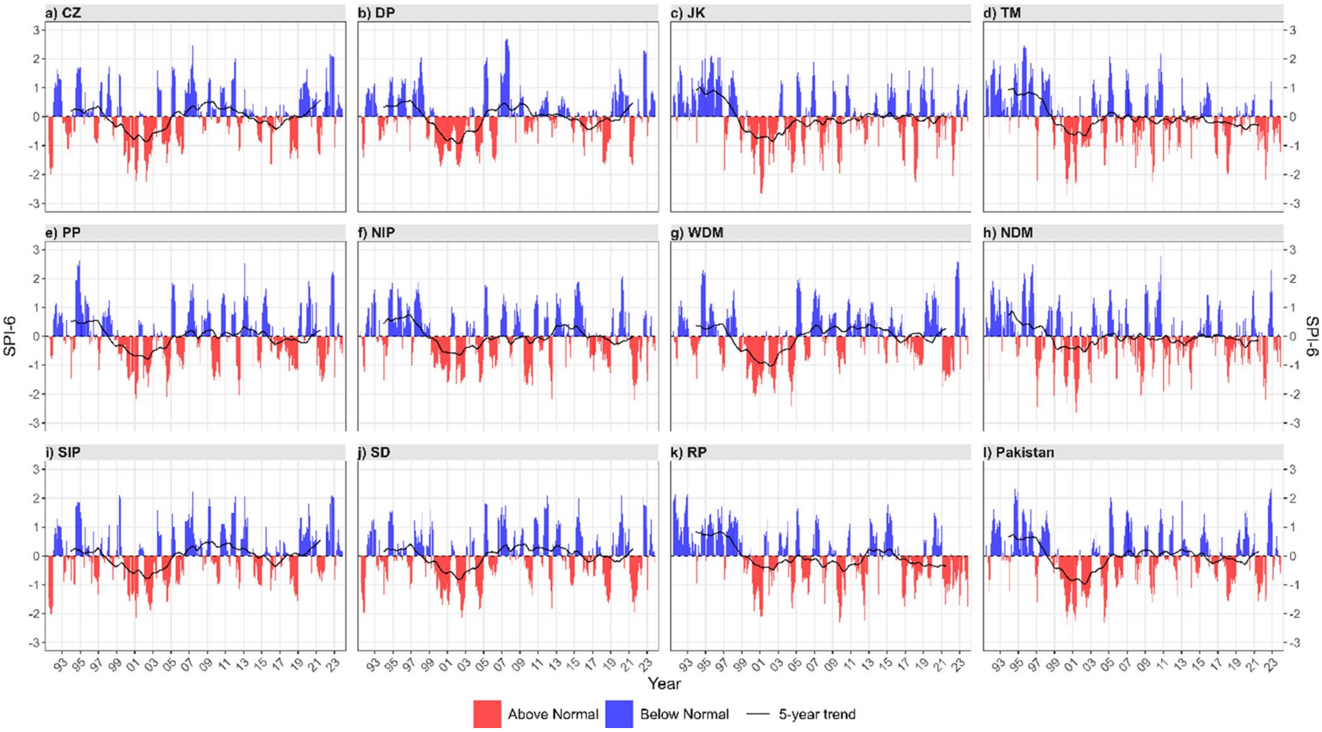

Fig. 8 6-month-sclae SPI-based drought analysis across Pakistan's AEZs: (**a**) Coastal Zone, (**b**) Dry Plateau, (**c**) Jammu & Kashmir, (**d**) Temperate Mountains, (**e**) Piedmont Plain, (**f**) Northern Irrigated Plains, (**g**) Western Dry Mountains, (**h**) Northern Dry Mountains, (**i**) Southern Irrigated Plain, (**j**) Sandy Desert, (**k**) Rainfed Plateau, (**l**) National Overview of Pakistan

an extreme dry 2001 and 2005, with recent severe drought in 2021 and 2022. The NDM saw extreme drought in 1997, 2001–2002, 2009, 2010 and 2022. In the SIP zone, extreme drought occurred in 1992, 2001, and 2003, alongside severe drought periods in 1997, 2005, and 2019. The SD faced extreme dryness in 1992, 2003, 2005, and 2022, with severe drought in other years. The RP experienced extreme droughts in 2001, 2010 and 2013 and severe drought continue from 2021 to 2023. Overall, Pakistan endured severe dry spells, particularly from 2000 to 2005, and most recently in 2018 and 202–2022, deeply impacting agricultural productivity across the nation.

3.6 SPI based drought analysis at the nine-monthly scale across the AEZs

The nine-month SPI analysis (Fig. 9) highlights widespread drought impacts across Pakistan's AEZs, affecting both hydrological and agriculture. The CZ faced extreme drought in 1992, prolonged dryness from 2000 to 2003, and severe droughts in 2005, 2006, and 2018. The DP endured extended drought from 1999 to 2005, with severe spells in 2006, 2018 and 2021. JK initially wet until 1998, experienced extreme droughts from 1999 to 2005 and again in 2005, 2008, 2018, and 2022. Similar drought episodes occurred in the TM (2000–2003, 2008, 2010, 2018, 2022), PP zone (1999–2005, 2010, 2018, 2022), and NIP (2000–2005, 2010, 2017–2018 2022). The WDM faced prolonged drought (1999–2005) and severe dry spells in 2010, 2018, and 2022, while the NDM saw extremes in 2000–2003, 2009, 2012–2014 and from 2018 to 2022. The SIP experienced drought spells in 1992, 2000–2006, 2015, 2019 and 2022; the Sandy Desert in 2003, 2005, and 2022. The RP, wet until 1999, faced spell 2000–2006, 2010, and 2013, with recent dryness from 2017 to 2023 and still continue. Overall, conditions remained wet until 1998, followed by persistent droughts (1999–2005), dry years in 2006, 2010, 2018, and a notable resurgence in 2022—emphasizing Pakistan's vulnerability to prolonged moisture stress and the urgent need for resilient water management.

3.7 SPI based drought analysis at the annual scale across the AEZs

The 12-month SPI analysis across the AEZs highlighting recurring drought patterns (Fig. 10). In the CZ zone, dryness occurred in 1992, 1994 with a prolonged severe drought from 1999 to 2003, followed by dry periods in 2005 and from 2015 to 2019. The DP zone experienced severe drought from 1999 to 2005, with another extended dry period from 2015 to 2019. JK remained wet until 1998, after which dry spell hit in 2000 and persisted through 2005,

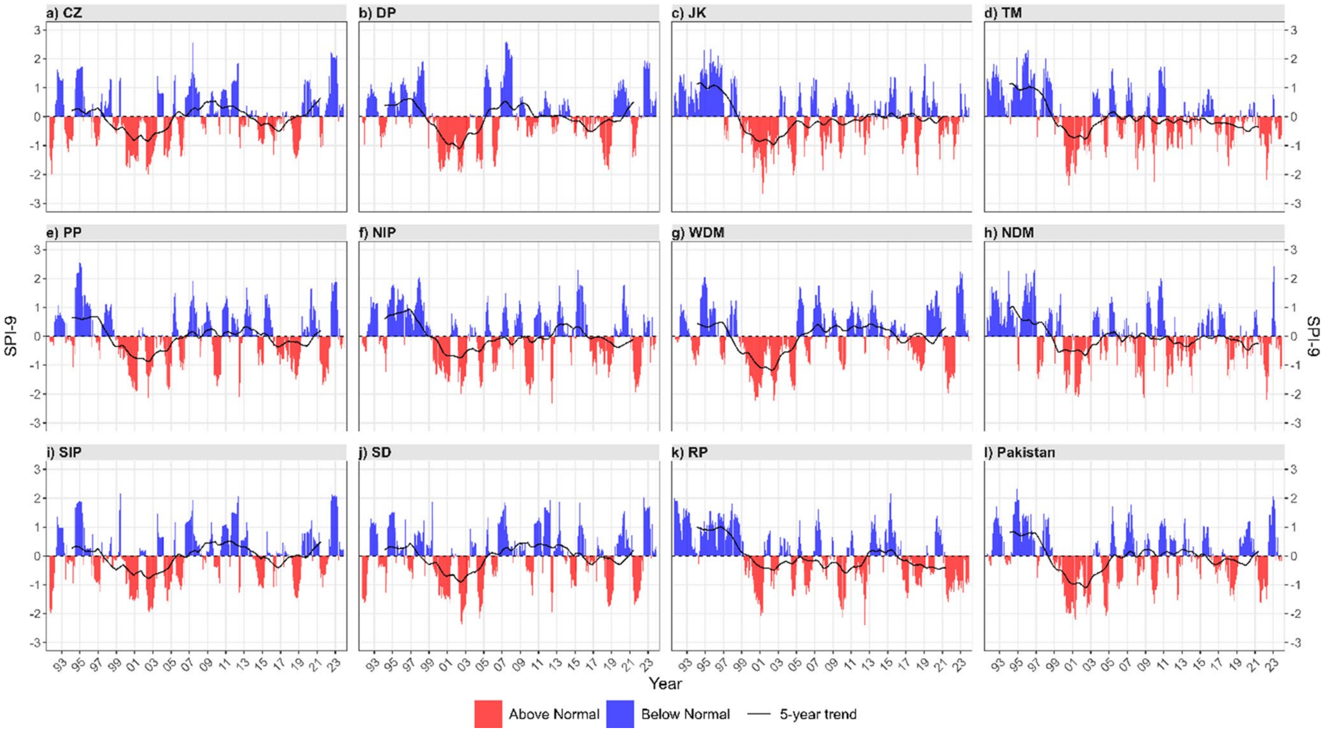

Fig. 9 9-month-scale SPI-based drought analysis across Pakistan's AEZs: (**a**) Coastal Zone, (**b**) Dry Plateau, (**c**) Jammu & Kashmir, (**d**) Temperate Mountains, (**e**) Piedmont Plain, (**f**) Northern Irrigated Plains, g) Western Dry Mountains, (**h**) Northern Dry Mountains, (**i**) Southern Irrigated Plain, (**j**) Sandy Desert, (**k**) Rainfed Plateau, (**l**) National Overview of Pakistan

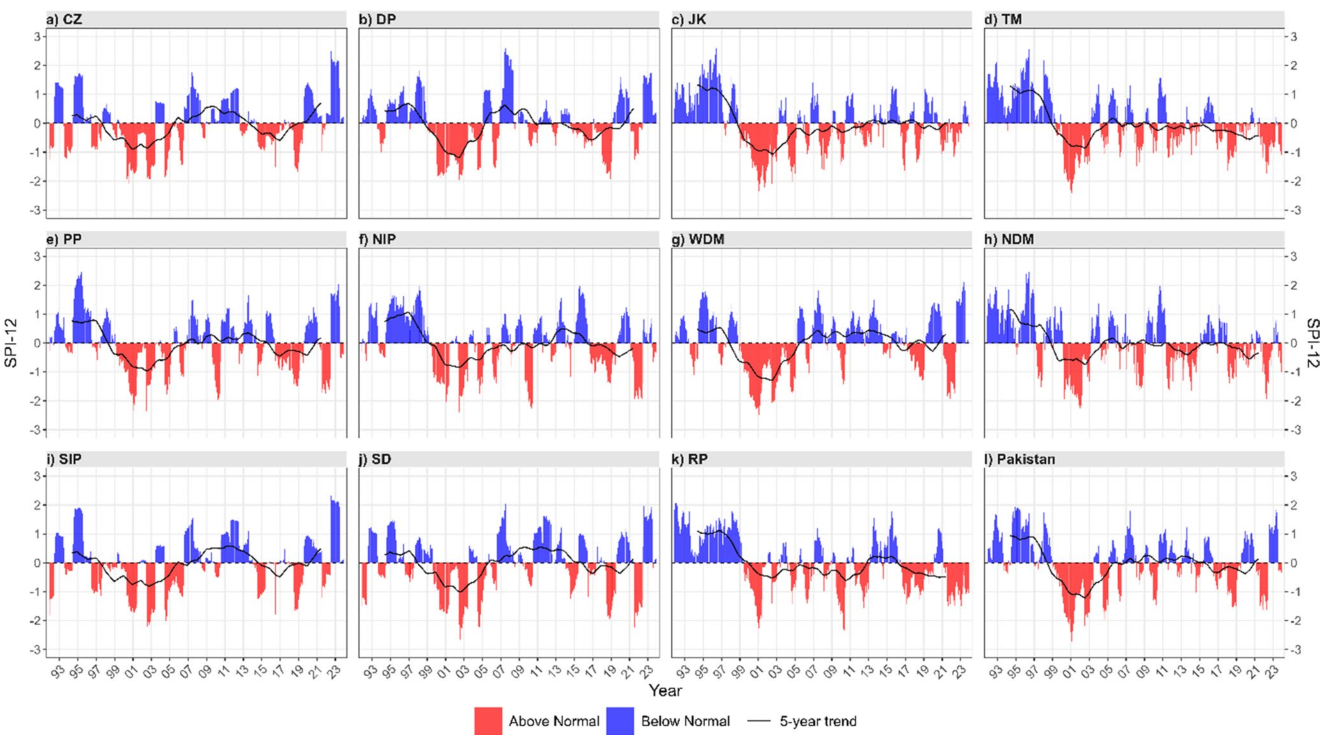

Fig. 10 9-month-scale SPI-based drought analysis across Pakistan's AEZs: (**a**) Coastal Zone, (**b**) Dry Plateau, (**c**) Jammu & Kashmir, (**d**) Temperate Mountains, (**e**) Piedmont Plain, (**f**) Northern Irrigated Plains, (**g**) Western Dry Mountains, (**h**) Northern Dry Mountains, (**i**) Southern Irrigated Plain, (**j**) Sandy Desert, (**k**) Rainfed Plateau, (**l**) National Overview of Pakistan

with more slight dryness in 2021–2022. The TM also shifted from wet to dry conditions from 1999 to 2003, followed by fluctuating moisture levels, and most recently, severe drought from 2021 to 2023. The PP saw prolonged drought from 1999 to 2005, extreme dryness in 2010, moderate drought from 2017 to 2019, and severe drought in 2022. In the NIP, dryness followed after 2000, with extreme droughts in 2003, 2005, and 2010, again dry spell from 2017 to 2019, and most recent dryness in 2022. The WDM experienced a prolonged drought from 1999 to 2005, again dryness in 2010, and most recent drought in 2022. The NDM faced droughts in 1998, followed by periods from 2000 to 2003, 2008, and 2012 to 2014, with continued dryness from 2018 to 2023. The SIP zone saw notable dry periods in 1992, 1997, 2000–2006, with slight dryness in 2022, but signs of recovery in 2023. The SD endured extreme droughts in 2000–2001, 2003, 2005, 2019, and 2022. The RP faced dryness from 2000 to 2001, extreme drought in 2010, and a severe dry period from 2017 to 2019, with a return to dryness and still continue from 2022 to 2023. Overall, Pakistan experienced severe drought from 1999 to 2003 and again in 2005 after slight recovery in 2004, extreme events in 2001, 2003, 2005, and 2010, and another dry phase from 2017 to 2019, and most recent drought in 2022.

4 Discussion

This study investigates spatio-temporal patterns of precipitation and air temperature anomalies and conditions, as well as drought variability across multiple timescales (3-month, 6-month, 9-month, and 12-month periods) from 1991 to 2023, focusing on the Agro-Ecological Zones (AEZs) in Pakistan, enabling the identification of critical changes in climatic conditions and their implications for agriculture and water resources in the country.

In 2023, deviations from long-term precipitation patterns included sharp declines in February and August, marking the driest conditions recorded since 1991, adversely affecting drought-prone AEZs such as the TM, RP, NDM and northern region of NIP. In contrast, a substantial increase in precipitation in May and July caused severe flooding across the country, especially in Jammu and Kashmir, where a precipitation surplus was linked to flooding events. A previous study by (Adnan and Ullah 2022) found significant increasing trends in Punjab and Khyber Pakhtunkhwa (KP) provinces in February and June. All the drought indices showed significant positive trends over Punjab and KP, whereas negative trends were observed in Jammu and Kashmir. Another study(Adnan et al. 2017b) observed that annual precipitation trends show a significant increase of 0.828 mm/year in arid regions, with monthly precipitation decreasing in January, May, July, and September, while increasing in other months. The observed deficit in precipitation is in the months of winter (December, February) in the AEZ's of TM, RP, NDM and northern region of NIP while slight deficit in SIP, SD and DP and surplus in precipitation observed in the month of summer (May, June, July) in the AEZ of JK and slight surplus in NIP, WDM, DP.

The temperature anomalies in 2023 revealed notable warming across several months, particularly in February, August, September, and December, while January, April and May recorded cooler-than-average conditions. The AEZ's of SD, RP, TM, eastern JK and DP experienced severe to extreme warming, highlighting increasing air temperature stress and drought risks. At the provincial level, (Adnan and Ullah 2022) found increases in maximum temperatures in Baluchistan (0.019 °C/year), Azad Jammu Kashmir (0.010 °C/year), and Gilgit-Baltistan (0.011 °C/year). Similarly, a significant increase in minimum temperature trends was observed in Punjab, Sindh, and Baluchistan, with a decrease noted over Gilgit-Baltistan, Azad Jammu Kashmir, and Khyber Pakhtunkhwa. Another study by (Adnan et al. 2017b) showed that maximum temperature trends in arid regions increased by 0.014 °C/year, and in extremely arid and humid regions, by 0.018 °C/year. Maximum temperatures increased throughout the year, except in August, while minimum temperatures showed an increasing trend across all months (Latif 2024b) further observed that temperatures across the entire tropospheric column in Pakistan increased by 0.15 to 0.31 °C/decade, suggesting that this trend could serve as a metric for analyzing near-surface heating and its impact on crop health. The observed reduction in snow cover across northern Pakistan aligns with meteorological data indicating significant climatic shifts, notably rising summer temperatures and decreased winter precipitation (Hussain et al. 2023a, b, c).

The observed trends from both temperature and precipitation condition data indicate that while drought conditions were historically concentrated in Sindh and Baluchistan, they are now expanding into the agriculturally critical regions of Punjab. PCI and ATCI patterns over seven periods showed extreme drought conditions expanding from the CZ, SD, and SIP AEZ's located in Sindh and Baluchistan in past from 1991 to 2020 toward agriculturally region of NIP from 2021 to 2023. Other studies also observed that Baluchistan and Sindh were the most affected regions due to their arid climates, with drought severity higher during the Kharif season, while reduced drought severity correlated with increased yields for crops such as maize, sugarcane, and wheat across provinces (Hussain et al. 2023a). Also, according to(Hussain et al. 2023b) because of their dry and hyper-arid climates, the provinces of Sindh and Baluchistan are particularly affected by drought. A drought hazard map of Sindh by(Adnan et al. 2015a) also highlighted the northward movement of drought in Sindh, with an increasing frequency of mild droughts in northern Sindh and more intense and severe droughts in the southern region. Crop yield losses escalate with increasing drought severity, particularly in southern Punjab (Rahman et al. 2023b). In comparison to other regions of the country, the southern high-temperature zone is experiencing a quicker rate of annual temperature increase (Khan et al. 2019). Another study showed that mean temperatures (T_mean) across Punjab have risen sharply, in north to south of Punjab (Syed et al. 2021). Drought intensity also varies seasonally, particularly in Sindh, where mild to moderate droughts are common but intensify with the failure of monsoons or western disturbance-related rainfall (Ashraf et al. 2022).

One limitation of the ATCI is its inability to capture seasonal or diurnal temperature variability. This results from its reliance on aggregated temperature metrics derived from 5-year mean intervals (e.g., 1991–1995, 1996–2000) rather than daily or seasonal data. While this approach provides a stable baseline for assessing thermal stress, it assumes a static relationship between temperature extremes and thermal comfort over time. Like the original TCI, which does not take into consideration day-of-year or diurnal variation and instead depends on smoothed weekly temperatures and multi-year maxima/minima (AghaKouchak et al. 2015),the ATCI may overlook short-term or seasonal fluctuations that can significantly influence perceived or actual temperature stress. This limitation is particularly relevant in regions with strong seasonal temperature contrasts, where extreme events may not align well with the smoothed 5-year baseline used in the ATCI formulation.

Decision to use the SPI was based on the primary aim of the study—to isolate and analyze precipitation-driven meteorological drought patterns across Pakistan without the influence of additional climatic or hydrological variables. Indices like the Palmer Drought Severity Index (PDSI), Standardized Precipitation Evapotranspiration Index (SPEI), or the Drought Severity and Coverage Index (DSCI) incorporate factors such as temperature, evapotranspiration, and soil moisture, which, while valuable, could introduce complexity beyond the scope of this precipitation-focused analysis. However, we acknowledge that incorporating such indices in future research would offer a more holistic understanding of drought dynamics by capturing multi-factorial influences on drought severity and persistence.

The SPI analysis across various timescales (3-month, 6-month, 9-month, and 12-month) identified drought variability in Pakistan from 1991 to 2023, with extreme drought conditions frequently occurring, particularly during the periods of 1999–2005, 2010, 2018 and 2022. AEZ's of TM, RP, NDM did not recover toward wet condition and continuously experiencing drought from 2018 to 2023 while other zones shows some recovery toward wet condition with positive SPI values. Other studies also observed drought events in Pakistan during 2001–2003, 2006–2007, 2008, 2012, 2017, and 2018 have been extensively documented as critical periods of agricultural stress, highlighting the cascading impacts of drought on crop yields, soil health, and rural livelihoods (Hussain et al. 2023b). Another study indicated 2000, 2001, 2002, 2015, and 2018 as severe drought years with the most intense and prolonged episode of drought, reaching an extreme category, occurred from 2000 to 2002, affecting over 60% of Pakistan's total area (Latif et al. 2024c).

This study utilized the ERA5-Land reanalysis dataset to compute the PCI and ATCI. Given the known limitations of remote sensing-based datasets—particularly their tendency to underestimate heavy rainfall and overestimate light precipitation—the selection of ERA5 was supported by recent validation efforts conducted within Pakistan. For example, at monthly (0.92), seasonal [0.89 (summer) to 0.98 (winter)], and annual (0.87) timescales, ERA5 shows a relatively good positive linear relationship with surface precipitation gauge data(Iqbal et al. 2022). Likewise, it was discovered that ERA5 accurately records both light and extreme precipitation events, closely matching rain-gauge readings throughout Pakistan (RC: 0.67, R: 0.81, RMSE: 1.69 mm) (Arshad et al. 2021).

The shift in climate patterns poses a significant threat to crop productivity and food security in Pakistan, making urgent adaptive measures essential to mitigate the effects of rising temperatures and increasing drought frequency. The findings highlight a troubling trend of escalating drought severity and expansion, particularly in vital agricultural regions like the northern irrigated zone in Punjab, which endangers water resources and food security. By applying SPI at 3, 6, 9-, and 12-month scales, we capture both acute and chronic drought episodes—short-term deficits that stress crops during key phenological stages and long-term deficits that undermine water storage, soil health, and ecosystem resilience.

Prolonged droughts in our study period were driven by recurring La Niña events and regional climatic variability. From 1998 to 2001, Pakistan endured one of its worst droughts—linked to a sustained La Niña cold phase in the Pacific—which wrought severe economic disruption and caused widespread human casualties and livestock losses (Azam Hayat Khan 2004). As noted by FAO, La Niña typically brings belowaverage precipitation to Pakistan's rainfed plains, sharply reducing rainfall during the wheat growing season and threatening yields also in the northern parts of the country, reduced snowfall during the winter months may reduce the availability of irrigation supplies and soil moisture in the spring that normally comes from snow melting (FAO 2021).

Specifically, we recommend deploying drought-tolerant crop varieties in arid zones, enhancing waterharvesting and storage infrastructure across semi-arid regions, and realigning sowing calendars with the evolving rainfall regime. Pakistan is the third-largest groundwater user globally, with over 70% of its irrigated area dependent on it, especially in Punjab, which accounts for more than 90% of national abstraction. The widespread use of groundwater in the absence of regulatory oversight poses serious sustainability challenges (Qureshi 2020). Using less water may slightly reduce yields, but it also cuts costs and makes farming more resilient, showing that smart water-saving methods can help sustain agriculture under climate stress (Ashofteh et al. 2017). By embedding these targeted, locale-specific strategies, we strengthen the study's emphasis on sustainability and adaptive capacity and highlight the practical relevance of our findings for climate-resilient agricultural planning.

5 Conclusion

This study highlights the growing climatic variability across the AEZs in Pakistan, emphasizing significant shifts in precipitation and air temperature patterns from the 1990s to the 2020s. Using a combination of drought indices (SPI, PCI, ATCI) and anomaly analysis, we reveal that drought conditions, once confined to arid regions like Sindh and Balochistan, are now encroaching upon the agriculturally critical areas of Punjab. This expansion poses serious risks to crop productivity and food security. The findings call for urgent policy attention toward climate-resilient agriculture and water resource management. We recommend enhancing seasonal forecasting systems and introducing AEZ-specific climate risk insurance. In water-stressed regions, especially Punjab's Northern Irrigated Plains, we propose piloting soil moisture sensors integrated with drip or sprinkler irrigation to optimize water use. Additionally, neighbourhood-based agroforestry initiatives should be promoted around urban and agricultural zones to mitigate temperature extremes, reduce runoff, and improve soil moisture, while also supporting carbon sequestration and diversified livelihoods.

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Author contributions R.M.U. and S.A. wrote the main manuscript text, contributed to data processing, analysis, and figure preparation. M.F.B., A.A., and M.A. helped with review and editing. All authors reviewed and approved the final manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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