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RESEARCH ARTICLE

Long-term rainfall changes based on multiple observation stations in Eastern Nepal

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ABSTRACT

This study utilized 32 meteorological stations for rainfall analysis in Eastern Nepal over 42 years (1977–2018). It found significant fluctuations in seasonal to decadal rainfall. The study revealed that most rainfall occurs during the monsoon season. The northeastern region of Eastern Nepal has received heavier rainfall. The analysis revealed both excess and deficit monsoon rainfall events across various seasons. The year 1987 recorded the highest monsoon rainfall, while 1982 experienced the lowest. In total, eleven major deficit events and seven major excess rainfall events were identified throughout the study period. The deficit years primarily occurred between the late 1970s and mid-2010s, while the excess years were largely concentrated between the mid-1980s and early 2010s. The decadal analysis has indicated that monsoonal rainfall has decreased gradually in Eastern Nepal during the past four decades. The cause might be the changing climate indices. The Southern Oscillation Index (SOI) was strongly correlated with monsoon rainfall; this relationship was particularly pronounced in large deficit and excess events compared to the usual conditions.

Keywords: ***Deficit, Excess, Monsoon, SOI, Variability, Eastern Nepal***

INTRODUCTION

Variability in rainfall is influenced by climate phenomena such as the El Niño-Southern Oscillation (ENSO), which affects the intensity of the monsoon (Balme and Jadhav, 1984; Sein et al., 2015). The Indian Summer Monsoon Rainfall (ISMR) exhibits substantial inter-annual variability influenced by large-scale ocean-atmospheric phenomena such as the ENSO and the Indian Ocean Dipole (IOD) (Sabeerali et al., 2019; Webster et al., 1999). Research suggests that the warming of the Indian Ocean has contributed to increased extreme monsoon precipitation in the past couple of decades. The ongoing warming of the Indian Ocean and the Indian subcontinent plays a significant role in increasing extreme rainfall in the changing climate of South Asian regions (Jin and Wang, 2017). Due to the warming of the climate in South Asia, over the past couple of decades, it has been affected by droughts in India, Nepal, and

Bangladesh (Kumar et al., 2013; Bagale et al., 2021; Chaudhary, 2003). The increased flood and drought events make the livelihood of the poor people complex in this region (Revadekar et al., 2012). More research is essential to decrease the effects of extreme events in these regions. Previous studies have demonstrated a complex relationship between the IOD and ENSO, which influences rainfall patterns in South Asia (Ashok et al., 2003; Sein et al., 2015; Sigdel and Ikeda, 2012). Understanding these trends is critical for managing climate-induced risks and enhancing resilience. These climate drivers can lead to significant fluctuations in monsoon rainfall from year to year, impacting agricultural practices and water availability in South Asia as well as in Nepal (Bagale et al., 2021; Revadekar et al., 2012; Gentle and Marasini, 2012).

In Nepal, recent studies have indicated an increasing extreme precipitation events across various regions of the nation (Bagale et al., 2025; Bhattrai et al., 2025; Gaire et al., 2024; Bagale et al., 2024). Bagale et al. (2025) investigate the deficit and excess events in western Nepal using 28 met stations. The study reveals that the extreme drought years were identified in 1977 and 2004. Gaire et al. (2024) identified far western region received the heavier rainfall than the other parts. There has been a decrease in seasonal rainfall in the Kathmandu Valley in recent decades, which lies in central Nepal (Bhattrai et al., 2025). Bagale et al. (2024) identified the winter drought in Nepal. The results prefer that eastern Nepal was affected by drought than other regions in the past decades. Rainfall plays a crucial role in water availability, agriculture, and socio-economic conditions in Eastern Nepal, where it is influenced by ISMR from June to September, which accounts for most of the annual rainfall. Extreme rainfall events can lead to rapid runoff and soil erosion, exacerbating the risk of natural disasters. Studies indicate an increase in extreme rainfall events, which heighten the risk of drought, flooding, and climatic risk (Wang et al., 2020). In addition to examining historical data trends, this study will utilize statistical methods such as time series analysis and anomaly detection to quantify changes in rainfall patterns over time. This approach will facilitate a deeper understanding of how extreme precipitation events affect Eastern Nepal.

The analysis of rainfall in the present study across Eastern Nepal provides a valuable opportunity to comprehensively explore these dynamics. Examining monsoon anomalies and the relationship between monsoon rainfall and SOI records over four decades. This study aims to identify patterns of rainfall variability in Eastern Nepal.

MATERIALS AND METHODS

Study Area

Eastern Nepal lies from about 26.5° to 28° N latitude and about 85° to 88° E longitude. Elevations range from about 60 meters south to 8774 meters in the north (Fig.1). The Eastern region experiences four seasons: winter, pre-monsoon, monsoon, and post-monsoon. The 32 meteorological stations were used for the Eastern region of Nepal (Fig. 1).

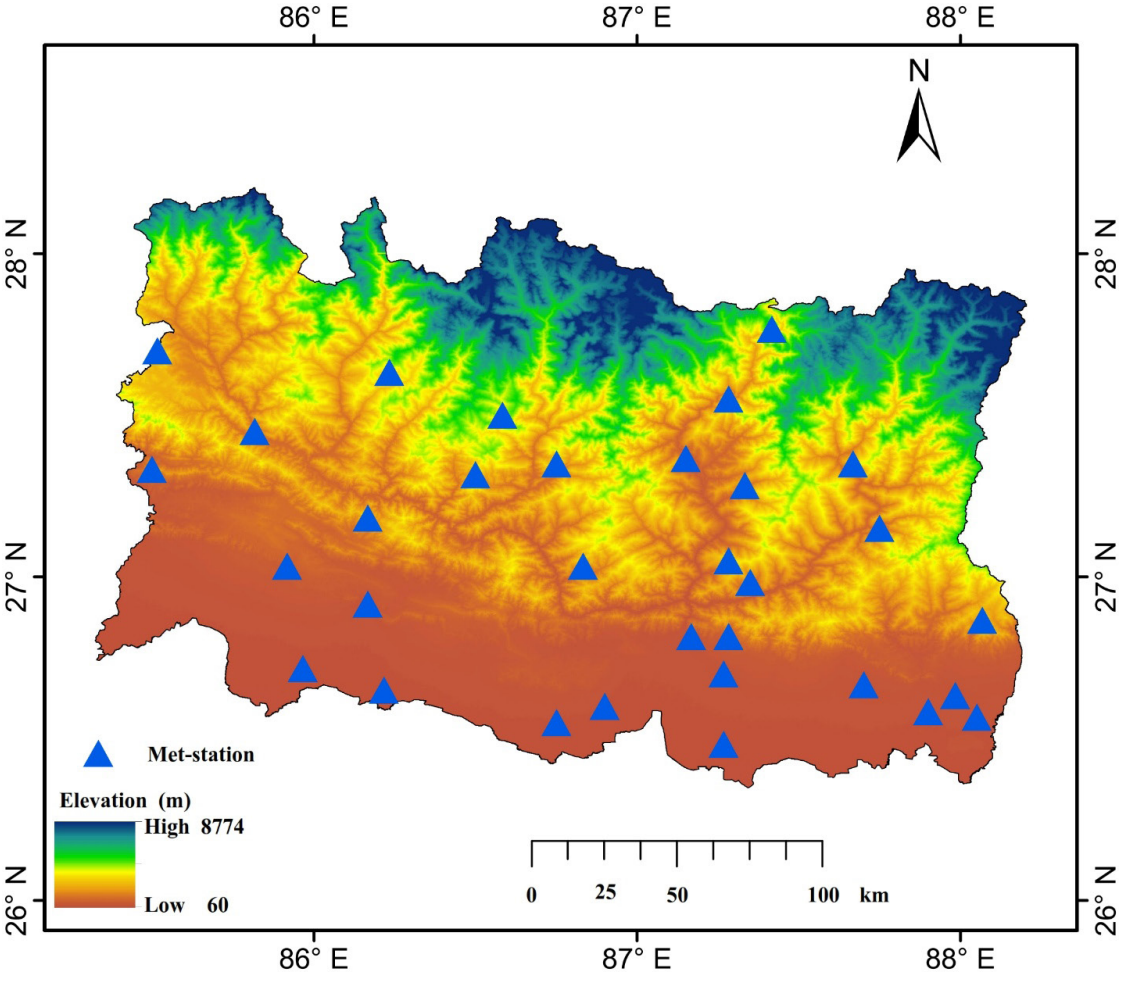

Fig. 1: Spatial distributions of meteorological stations in Eastern Nepal

DATA USED AND METHODOLOGY

The Department of Hydrology and Meteorology (DHM) of Nepal provided the daily rainfall data from 32 meteorological stations in Eastern Nepal between 1977 and 2018. The stations are chosen based on a uniform spatial distribution and data availability. The monthly total rainfall figures were calculated by adding the daily rainfall data. Similarly, the annual total rainfall figures were calculated by adding the monthly total rainfall data from January through December. Once the missing data were filled in, the annual rainfall at stations was determined. The arithmetic mean was used for the average monthly, seasonal, and yearly rainfall. This paper used the Normal Ratio method to estimate missing rainfall values and Student's t test to check statistically significant of rainfall (Bagale et al., 2023a; Bagale et al., 2023b). Spatial variability of rainfall was visualized by using inverse distance weighted method (Patel, et al., 2007). The monthly SOI data over the Nino 3.4 regions were acquired from https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml.

RESULTS

Rainfall Statistics:

The average monthly rainfall from January to December in eastern Nepal is displayed in figure 2. With 495.54 mm on average, July has the most rainfall, followed by August with 397.37 mm. Rainfall from June to September is noticeably higher than during other months. With 9.97 mm on average, December has the least amount of rainfall. Rainfall gradually increases from March through July, then gradually decreases from August through December. Wet summers and dry winters are the hallmarks of the region's normal monsoon cycle, which is consistent with this trend.

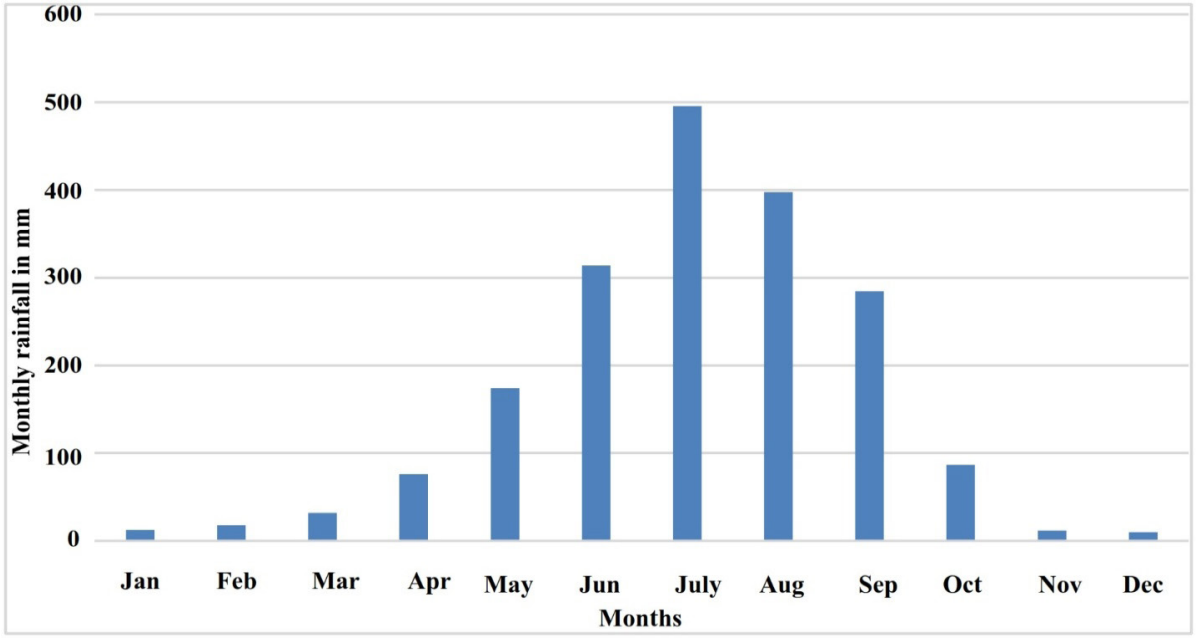

Fig. 2: Average monthly rainfall (mm) from 1977 to 2018

The monsoon season accounts for 78.01% (1491.19 mm) of Eastern Nepal's annual rainfall (1911.53 mm), followed by the pre-monsoon 14.75 %. Similarly, winter is 2.11 % across eastern Nepal, which is the lowest seasonal rainfall, whereas post-monsoon yields 5.13 %, (Table 1). The spatial variability of monsoon months is depicted in Fig. 3(a, b, c, and d).

Table 1: Average Season-wise Rainfall in Eastern Nepal from 1977-2018

Season	Winter	Pre-monsoon	Monsoon	Post-monsoon
Average rainfall (mm)	40.28	281.94	1491.19	98.12

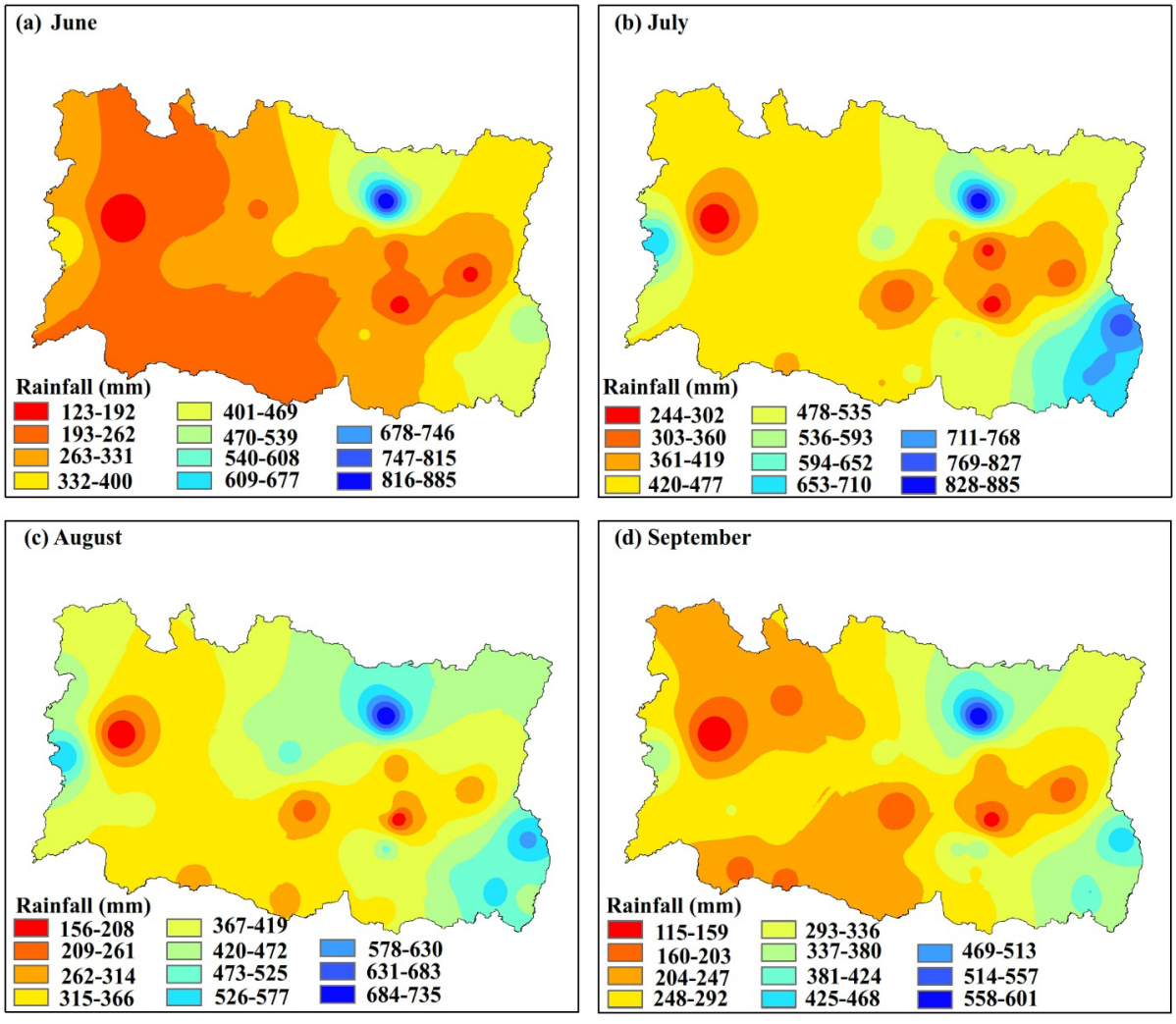

Fig. 3: Spatial variability of mean rainfall during (a) June, (b) July, (c) August, and (d) September from 1977 to 2018

The monthly rainfall variability for June to September is clearly shown in fig (3a, b, c, and d). In June, the northeastern highlands received more rainfall, with a large range of variability, from 73 mm to 318 mm. Similarly, the eastern region received more rainfall during July, decreasing towards the central parts. A similar rainfall pattern is shown (Fig. 3c, and d) in August and September, where the rainfall amounts are different.

Spatial Variability of Seasonal Rainfall

Winter rainfall ranged from 18 mm to 131 mm (Fig. 4a). The northeastern regions receive the most, while the eastern highlands also get relatively high amounts. In contrast, the southern lowlands receive the least. Pre-monsoon rainfall also shows wide variation, from less than 134 mm to more than 944 mm (Fig. 4b). The northern and central areas receive lower amounts during this season. Monsoon rainfall in Eastern Nepal varies greatly, ranging from 638 mm to over 3106 mm (Fig. 4c). The north-central

part records the lowest rainfall, while areas known as "monsoon pockets" receive the highest (Fig. 4c). Post-monsoon rainfall ranges from under 39 mm to over 257 mm (Fig. 4d). The south and north eastern areas receive more rain during this period. The lower eastern region gets the highest rainfall, while the northeast receives the least.

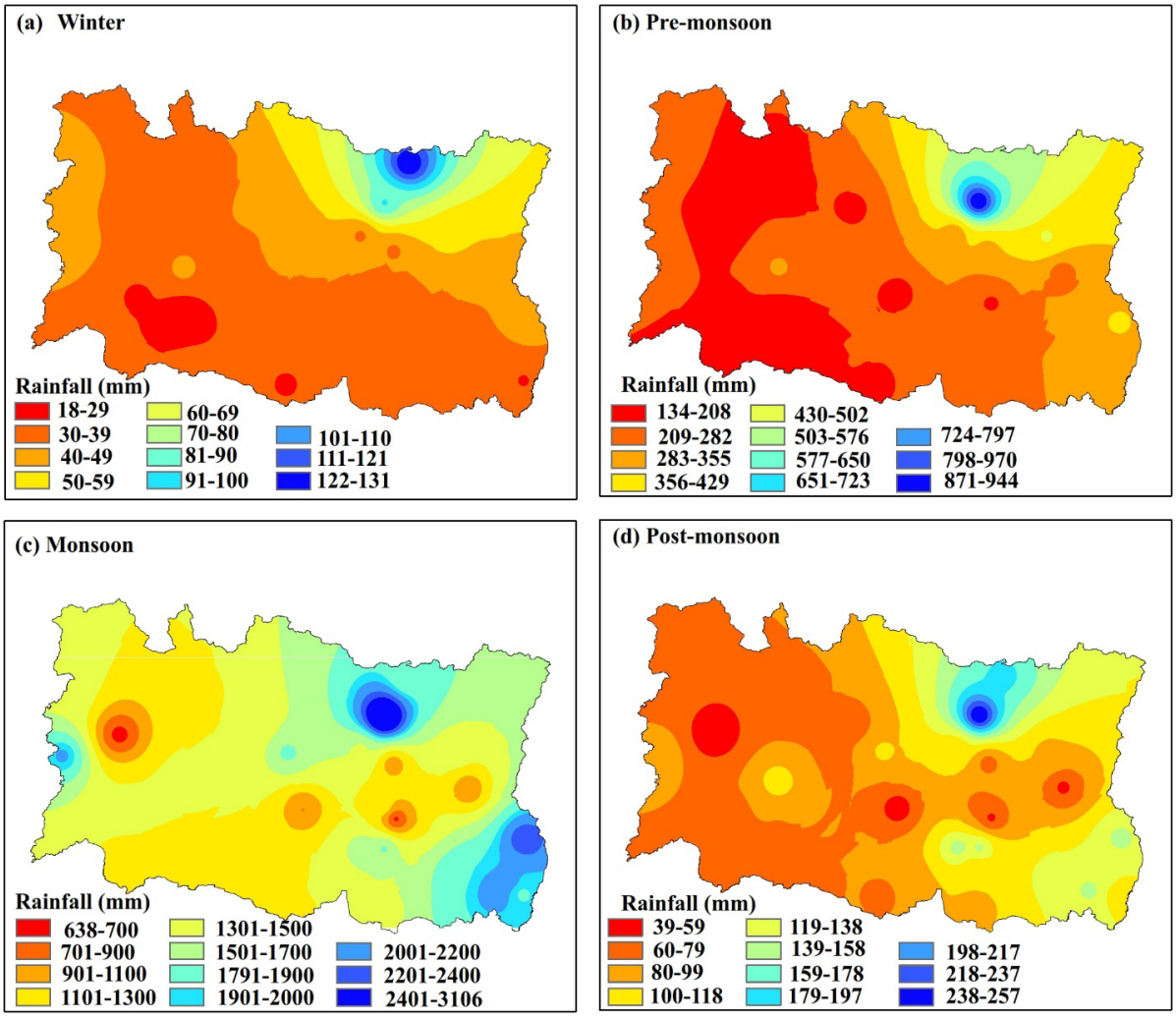

Fig. 4: Seasonal spatial variability of mean rainfall for (a) winter, (b) pre-monsoon, (c) monsoon, and (d) post-monsoon, from 1977 to 2018

Spatial Variability of Annual Rainfall

The high mountainous areas of eastern Nepal received high rainfall, particularly in the northeastern part has the highest rainfall, and the lower lowlands have the minimum. Figure 5 shows the variability of rainfall from 848 mm to more than 4400 mm in the northeast region.

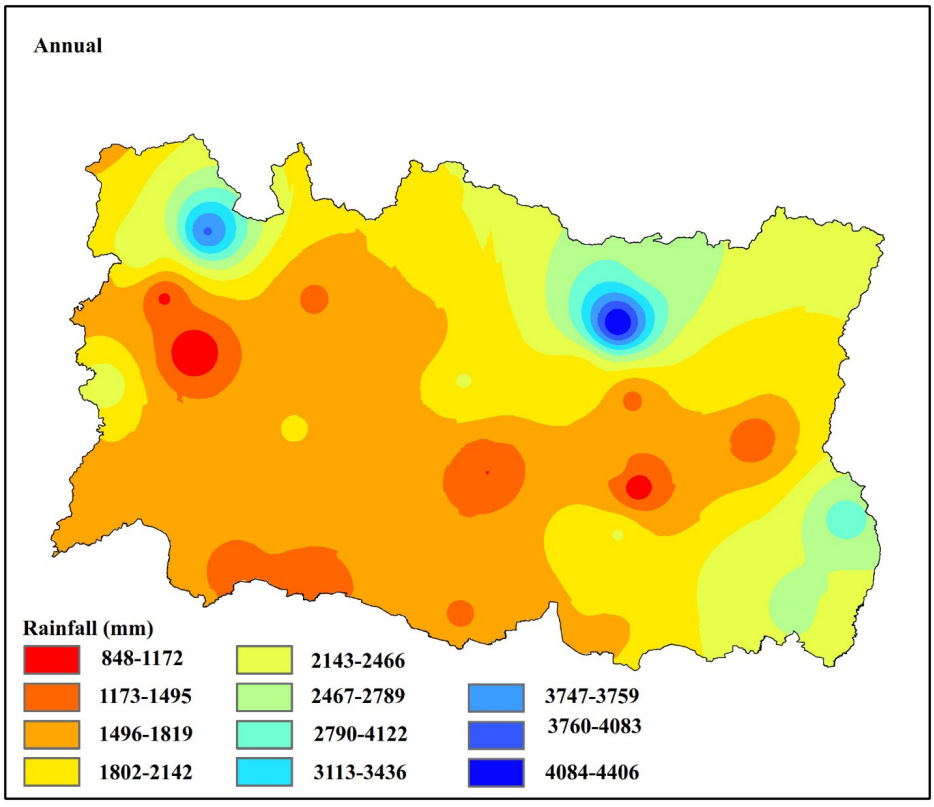

Fig. 5: The mean annual rainfall is spatially distributed in Eastern Nepal (1977-2020)

Temporal Variability of Rainfall

Eastern Nepal experiences significant annual variations in rainfall from 1977 to 2018. The average annual rainfall was 1911.53 mm. A notable deficit occurred in 1982 and an excess in 1987. The overall rainfall pattern is shown in figure 6.

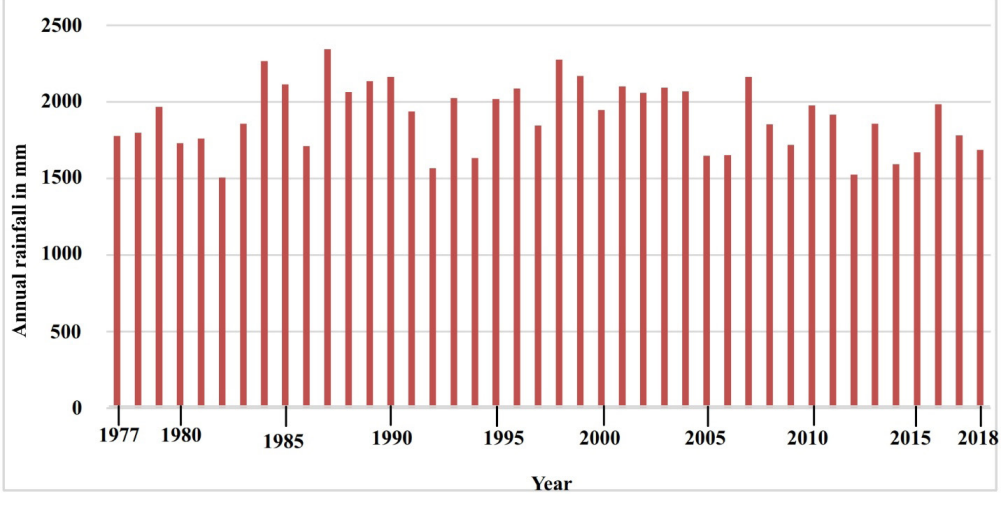

Fig. 6: Temporal variability of mean annual rainfall from 1977 to 2018

Monsoon Rainfall and Anomalies

Figure 7a shows large year-to-year changes in monsoon rainfall, with 1987 having the highest and 1982 the lowest. On average, eastern Nepal receives about 1491.19 mm of rainfall during the monsoon. Fig 7b displays monsoon rainfall anomalies in eastern Nepal. The largest negative anomalies (drier years) occurred in 1982 and 2012, while the highest positive anomalies (wetter years) were in 1984 and 1987. Positive values show above-average rainfall (wet years), while negative values indicate below-average rainfall (dry years). The graph highlights the strong annual variation in monsoon rainfall over the years.

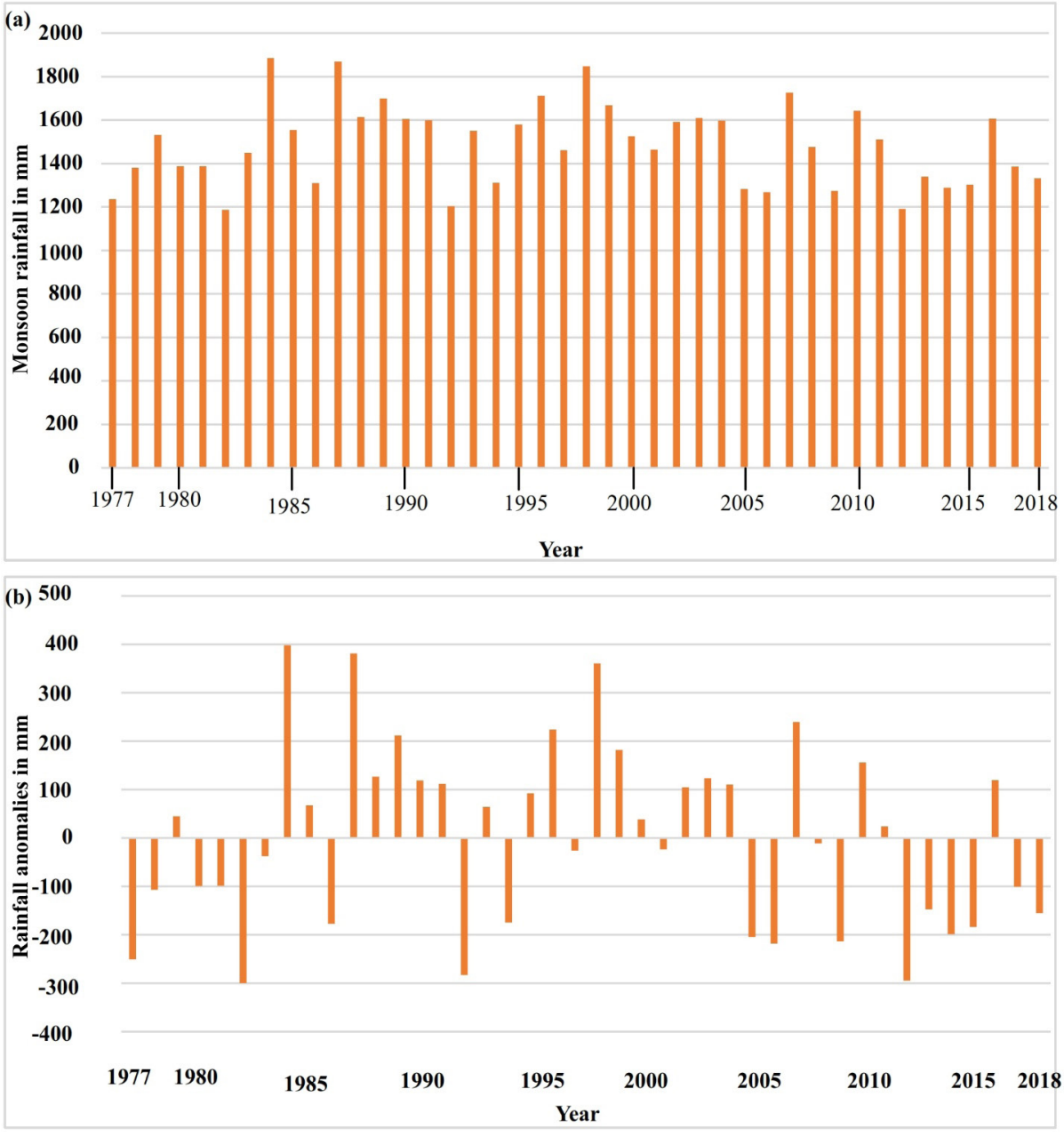

Fig. 7: Temporal variability of (a) mean monsoon rainfall and its anomalies (b) from 1977 to 2018

Decadal Rainfall of Monsoon

This study also examined the changes in decadal rainfall. Over the four multi-decadal periods (1981-1990, 1991-2000, 2001-2010, and 2011-2018), monsoon rainfall varied greatly across the region. The northwest consistently received less rainfall each monsoon season, while the northeast saw more than 3000 mm. Overall, the eastern region experienced higher monsoon rainfall compared to other areas. Figures 8a-d illustrate this significant decadal variation in rainfall across eastern Nepal.

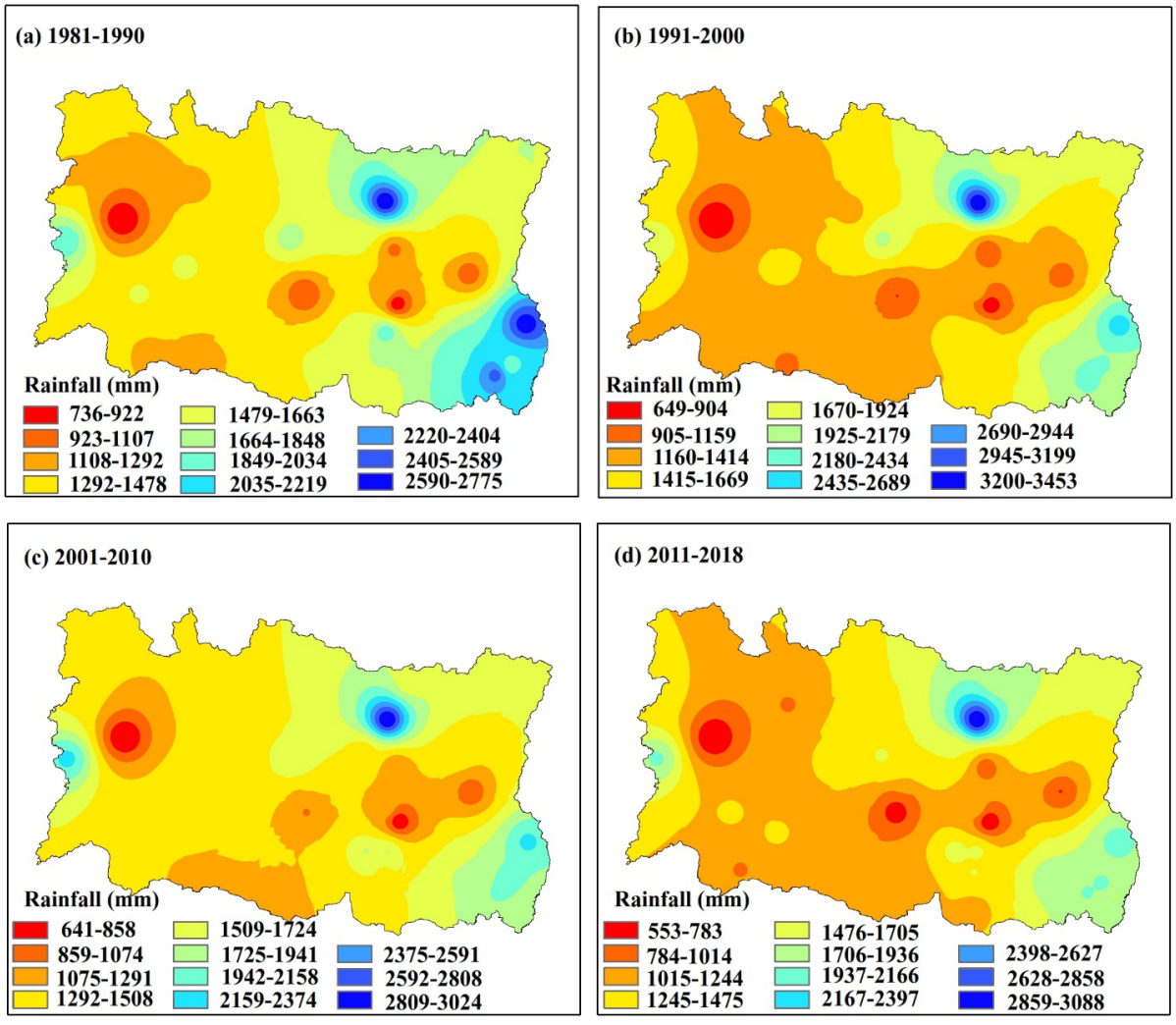

Fig. 8: Spatial rainfall distribution in multi-decadal windows (a) 1981-1990, (b) 1991-2000, (c) 2001-2010, and (d) 2011-2018 over Eastern Nepal

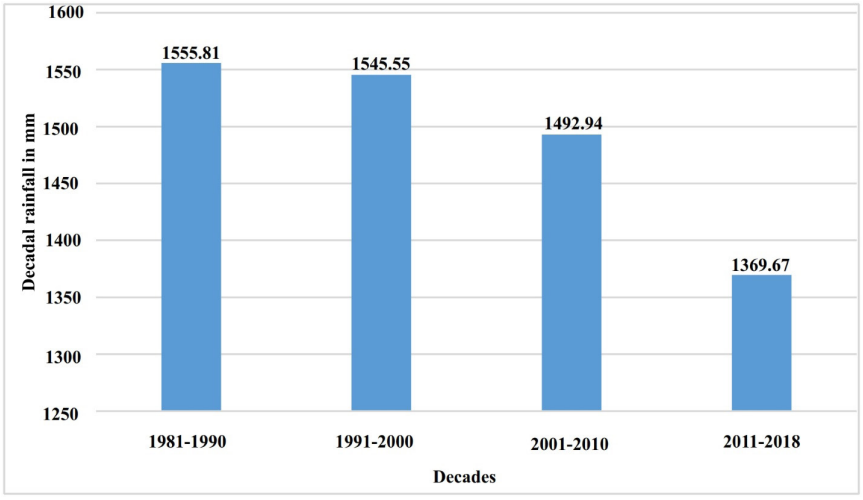

Fig. 9: Decreasing rainfall in the past four decades in Eastern Nepal

The mountainous areas of the eastern region showed consistently heavy rainfall patterns, as seen in Figures 8a-d. In contrast, the southern lowlands were much drier compared to other parts. Overall, the heaviest rainfall occurred in the mountain regions. However, there has been a gradual decline in average decadal rainfall across eastern Nepal over the past four decades (Figure 9).

Relationship between Monsoon Rainfall and SOI

The comparison between the standardized monsoon rainfall and the summer SOI series shows that the correlation coefficient between the standardized monsoon rainfall and summer SOI is 0.36 at a 95 percent confidence level. The standardized monsoon rainfall and the summer SOI series are moderately correlated in eastern regions. The correlation results supports by (Bagale et al., 2023), where description of relationship between monsoon rainfall and SOI are described trolley. The monsoon rainfall is influenced by the SOI in Eastern Nepal.

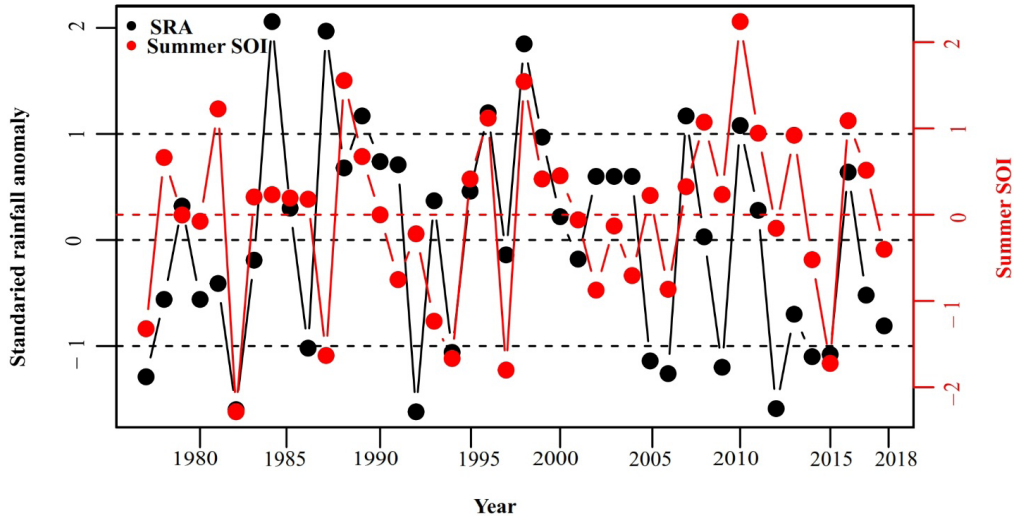

Fig. 10: Relationship between standardized summer rainfall anomaly and southern oscillation index

Based on standardized anomalies, this study has found a total of eleven large rainfall deficit episodes (1977, 1982, 1986, 1992, 1994, 2005, 2006, 2009, 2012, 2014, and 2015). Similarly, seven large excess rainfall episodes (1984, 1987, 1989, 1996, 1998, 2007, and 2010) occurred in different years throughout the study period. The temporal variability of monsoon large deficit and large excess years is shown in Figure 10 for the eastern region. The results have been supported by previous studies (Bagale et al., 2021; Bagale et al., 2023b).

Extreme Rainfall in Eastern Nepal

The large excess and deficit first and second events, spatial variability of rainfall, are depicted in figure 11 (a, b, c, and d). In the dry year of 1982, severe drought conditions were widespread across eastern Nepal (Fig.11a). During dry years, the lower regions still received the highest rainfall, with amounts ranging from 981 mm to about 3300 mm. The total rainfall during the 1982 monsoon was around 1187 mm. A similar pattern occurred in another dry year, 1987 (Fig.11b). In contrast, during the wetter years of 1987 and 2012, the eastern region saw concentrated pockets of heavy rainfall in the northeast and lower areas (Fig. 11c and d).

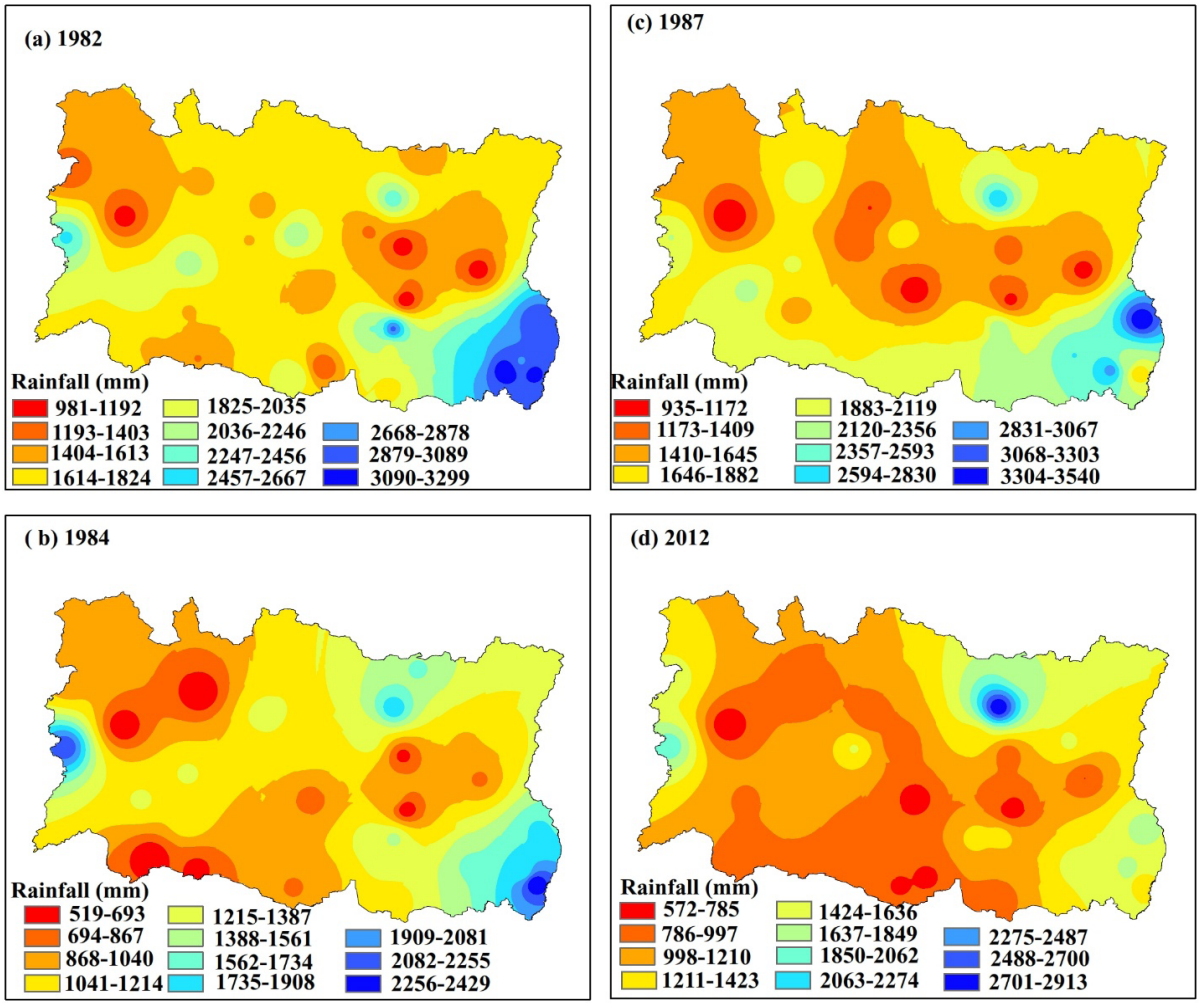

Fig. 11: Spatial variability of rainfall in extreme years (a) 1982, (b) 1987, (c) 1984, and (d) 2012

DISCUSSION

The study of rainfall (1977–2018) shows a significant increase from May, peaking in July due to the monsoon. Eastern Nepal receives 78.01% of its annual rainfall during this period, with high spatial variability, the northeast being the wettest. After 2000, consecutive dry years occurred were 2005 and 2006, and in recent years, 2014 and 2015. The findings of this study align with previous studies (Bagale et al., 2023).

North eastern region has received more monsoon rainfall because these parts faced the windward direction. The strong easterly winds support in monsoon and the westerlies in winter. The results support earlier studies (Sigdel and Ikeda, 2012; Ichiyanagi et al., 2007).

Previous studies in South Asia identified that in past decades, the dry monsoon years have been frequently observed in Myanmar and India (Sein et al., 2015; Kumar et al., 2013).These studies findings supports the decadal rainfall has decreased in eastern Nepal because the South Asian monsoon has been influenced by ENSO.

This study found that a total of eleven large deficit rainfall episodes and large excess rainfall episodes occurred in different years throughout the study period. Notable positive anomalies of around 21 % were observed in 1984. Conversely, approximately 25 % of strong negative anomalies were seen in 1982. The results are in line with (Sharma et al., 2020). The extreme events' similarity has been observed in India and Myanmar (Kumar et al., 2013; Sein et al., 2015).

A four-decade analysis of rainfall data from Eastern Nepal examines long-term rainfall variability, extreme events, and their links to climate drivers like ENSO. The results are similar to (Bagale et al., 2023; Shrestha et al., 2000). Similarly, in India, in line with (Ashok et al., 2003; Sabeerali et al., 2019). The analysis shows that Eastern Nepal has experienced a notable decrease in rainfall since 1990, possibly linked to the weakening southwest Indian monsoon. Similar trends in monsoon rainfall decline have been observed in other parts of South Asia, with potential links to frequent El Niño events. The reduction in rainfall patterns has been consistent across South Asia, with similar findings reported in Myanmar (Sein et al., 2015) and India (Varikoden et al., 2015). Additionally, the frequent occurrence of El Niño events may be contributing to these rainfall declines (Bagale et al., 2021; Varikoden et al., 2015). This study emphasizes the broader trend of diminishing monsoon rainfall in the region.

CONCLUSION

The present study showed significant spatial and temporal rainfall variability. Seasonal contributions to annual rainfall were dominated by the monsoon (78.01%), followed by pre-monsoon (14.75%), post-monsoon (5.13%), and winter (2.11%). Monsoon rainfall varied notably year-to-year, ranging from about 1187 mm to 1884 mm. The highest rainfall was recorded in 1984, while the lowest occurred in 1982. Eight large excess years and eleven large deficit years were identified, with extreme anomalies reaching +25% and -21%, respectively. Decadal trends suggest a decline in monsoon rainfall in recent decades. The SOI tracks El Niño and La Niña events, showing a general but inconsistent relationship with monsoon rainfall variation, with higher SOI values often linked to wetter conditions.

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