Monsoon Rainfall Variability in Large Excess Years

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ABSTRACT

The present study used 107 meteorological stations' rainfall time-series data from 1977 to 2018, over different physiographic regions of Nepal. The normal ratio method was adopted to fill in missing datasets. Monthly, seasonal, and annual data analyses were carried out for each site in Nepal. Non-parametric Mann-Kendall test identified monsoon rainfall decreasing by 0.36 mm/monsoon in the recent four decades. The east-west mid-mountainous range observed the heavy monsoon rainfall. The average monsoon rainfall is 1433.42 mm. The present study identified the seven large excess episodes. Out of them, four large excess episodes (1998, 1999, 2000, and 2007) are conceded with La Nina events which quantify significant excess rainfall (19.21, 12.07, 14.29, and 14.79) percent respectively from average rainfall. The western region experienced less rainfall than the eastern and central regions throughout the seven major monsoon excess years. The mid-mountainous of central Nepal has received more rainfall. At a 95% confidence level, the correlation coefficient between monsoon rainfall and the southern oscillation index (SOI) is 0.52.
Keywords: Monsoon rainfall, Excess seasons, Nepal, SOI, Variability

Introduction

The El Niño-Southern Oscillation (ENSO) is the primary driver of climate fluctuations on an inter-annual scale, influencing global, regional, and local climates, including Nepalese monsoon rainfall (Fan et al., 2017; Bagale et al., 2023a). The Asian monsoon system varies across intra-seasonal, annual, and inter-annual timescales, with the rainy phase characterized by warm, moist winds from tropical oceans (Webster et al., 1998; Wang et al., 2020). Severe El Niño/La Niña events result in weaker or stronger monsoons and dry or wet conditions in South Asia. La Niña, associated with cooler Pacific Ocean surface temperatures, leads to heavier monsoon rainfall in Nepal, India, and Bangladesh (Bagale et al., 2021; Balme and Jadhav, 1985; Chowdhury, 2003). It also alters atmospheric pressure and storm activity, affecting hurricane and cyclone frequency. La Niña has major implications for agriculture, and water resources, as it impacts precipitation and temperature patterns. In contrast, El Niño, linked to warmer ocean temperatures, causes reduced rainfall (Varikoden and Babu, 2015; Wang et al., 2020).

In Nepal, many studies have been concentrated on rainfall variability (Shrestha, 2000; Ichiyanagi et al., 2007; Karki et al., 2017; Shrestha et al., 2019; Bagale et al., 2023a). Shrestha, (2000) used rainfall data from 60 stations in Nepal excluding Himalayan regions between 1957 and 1988, which noticed large monsoonal rainfall variability and identified the deficit and wet episodes. Ichiyanagi et al. (2007) found that monsoon rainfall decreases from east to west, with increased rainfall up to 2000 m and a decline at higher altitudes. Karki et al. (2017) observed a more frequent decrease in monsoonal rainfall in the eastern region. Shrestha et al. (2019) analyzed rainfall trends from 43 stations between 1981 and 2015. According to their findings, the majority of the stations in the Kaligandaki and Koshi river basins have seen a decline in the annual rainfall trend. A recent study by Bagale et al. (2023a) found a diminishing monsoonal precipitation pattern. With a few exceptions, a significant negative (positive) SOI value and deficiency (excess) precipitation in Nepal were positively correlated (Sigdel and Ikeda, 2012; Bagale et al., 2021). The previous researcher studied the monsoon rainfall characteristics from a different perspective than the large excess years. There is a research gap in spatial variability on monsoon rainfall of major excess episodes in Nepal. The previous studies did not summarize the rainfall variability of individual large excess summer monsoon episodes. Monsoon variability can influence water resources, flooding, and landslides, affecting the economy and the population's well-being. Furthermore, this study ranks the summer monsoon of Nepal based on rainfall anomalies.

This study's primary goal is to examine the 42 years of significant monsoon excess years linked to La Nina and normal years (1977-2018). Similar to that, the focus of this study was on the variations in rainfall across several regions throughout the monsoon season.

Materials and Methods

Study area

Nepal is a landlocked, mountainous nation located in South Asia’s central Himalayan region. Its latitude ranges from 26° 22´to 30° 27´ N and its longitude ranges from 80° 04´ to 88° 12´E (Fig.1). The country has an area of 147516 sq. km and measures 885 km from east to west and 130 km to 260 Km in north to south (Figure 1). Nepal's topography ranges from the lowland Terai at 60 meters to Mount Everest's 8848.86 meters in the Himalayas. The northern region contains the world's highest peaks. Major rivers like the Koshi, Gandaki, and

Karnali originate from the Himalayas, fed by glaciers, snowmelt, and monsoon rains.

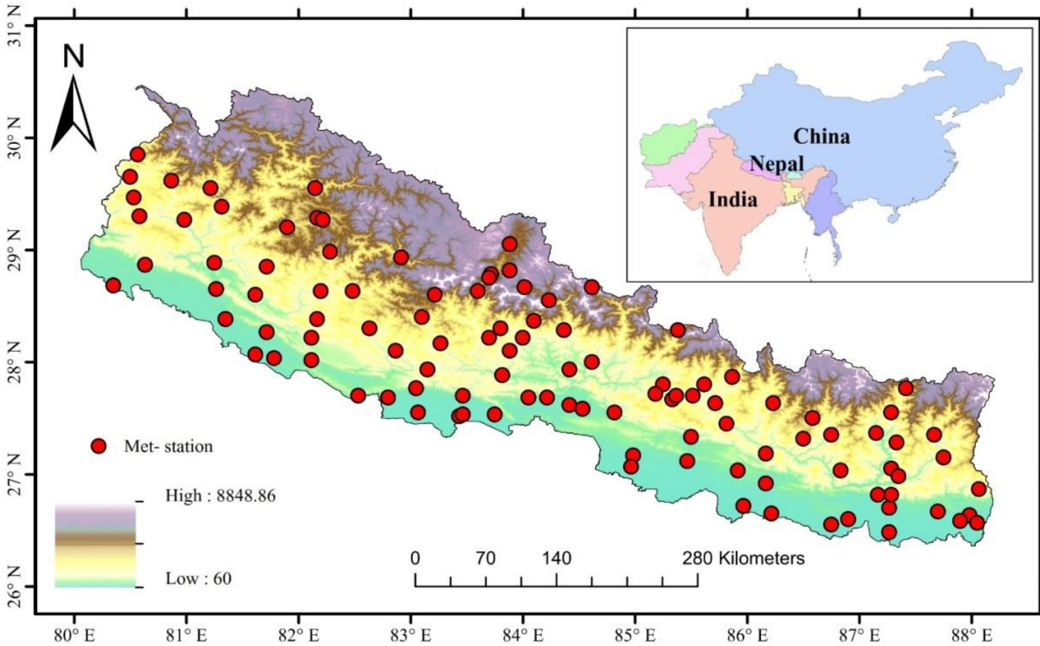

Figure 1: Study area with distributions of 107 meteorological stations.

Nepal has a sub-tropical climate, with the majority of its rainfall occurring during the monsoon season (JJAS) (Karki et al., 2015). Generally, annual precipitation decreases from east to west (Ichiyanagi et al., 2007).

Data and Methods

We have collected meteorological observation daily data from the Department of Hydrology and Meteorology (DHM) across the country. In this study, these data sets are used for the extreme events rainfall analysis. For this, initially, we have collected 120 station datasets for homogeneous distributions. After handling of quality of the data, we used only 107 stations for further analyses. The spatial variability of stations is shown in Figure 1. To estimate the missing rainfall values in the climate dataset from neighboring met-stations, this study used the Normal Ratio Method (Bagale et al., 2023b).

There are notable differences in air pressure between the eastern and western tropical Pacific during the El Niño and La Niña phases, which can be measured using the SOI (Yan et al., 2011). Tahiti's (Darwin's) below-normal (above-normal) air pressure is represented by the negative phase of the SOI. The monthly

SOI data and the sea surface temperature (SST) anomaly over the Nino-3.4 regions for the period from 1977 to 2018 are available at https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml. Based on the three-month running average SST anomalies over the Nino-3.4 zones, a year is considered to be La Niña when the Nino-3.4 SST anomaly value is less than 0.5°C in any five consecutive overlapping months. Detailed information on La Niña episodes can also be obtained from the mentioned source.

To determine the years of surplus and deficit, this study used a departure of ± 10 percent from the long-term average monsoonal rainfall (Bhalme and Jadhav, 1985; Varikoden et al., 2015; Sein et al., 2015). Furthermore, observed monthly rainfall datasets were used to formulate their standardized departures using the historical mean and standard deviations for the period 1977 to 2018. Standardized rainfall anomalies were used to identify the dry and excess episodes. The present study has visualized rainfall using the inverse distance weighted (IDW) method, there is no doubt that IDW interpolation carries out the premise that objects close to one another share more similarities than those farther apart (Patel et al., 2007).

We did the Student's t-test for the monsoon anomalies, and the results are at a 95 % confidence interval.

We applied the Man-Kendall (MK) test to assess trends in rainfall data, identifying significant increases and decreases over time. This method is used in climate studies (Talax et al., 2015: Gaire et al., 2024).

Results

Monsoon rainfall and its trends

Monsoon rainfall varies significantly across Nepal. The central and eastern mountainous regions experience complex, heavy rainfall, while the north-south region tends to be drier. Summer rainfall totals range from 200 mm in the northwest to over 3500 mm in the northeast and central mid-mountains, showing large spatial variability. Generally, the summer rainfall total increases as the altitude increases up to the mountainous region of Nepal (Figure 2a) at nearly 28.5 degrees altitude.

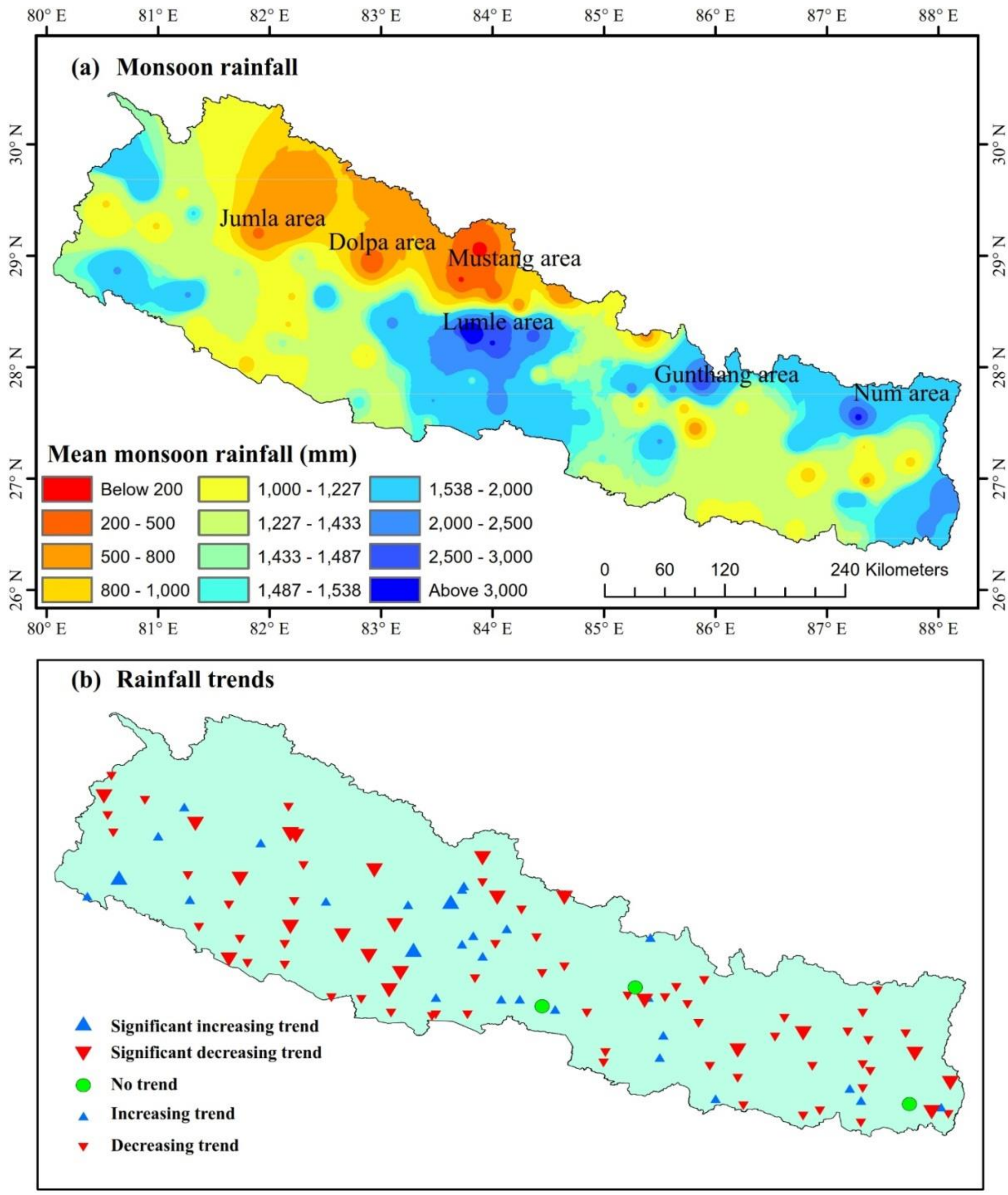

Figure 2: Shows the spatial distributions of (a) the average monsoon rainfall in Nepal from 1977 to 2018 and (b) the trends in monsoon rainfall in various regions of the country.

Furthermore, the nonparametric MK trend test identified station increasing or decreasing monsoon rainfall in different stations of the country (Figure 2b). Out of 107 stations, 29 show increasing trends, 54 decreasing trends, 2 significant increases, 21 significant decreases, and 2 no trends (Figure 2b). This study identified the decreasing trend of monsoon rainfall by 0.36 mm/monsoon during the last four decades. The central region's lowland and midlands stations show an increasing trend of rainfall than the other regions. However, the decreasing monsoon trends dominated the country.

Temporal variability of monsoon rainfall

This work computed monsoon rainfall and normalized anomalies using rainfall time series from 107 stations (Figures 3a, b).

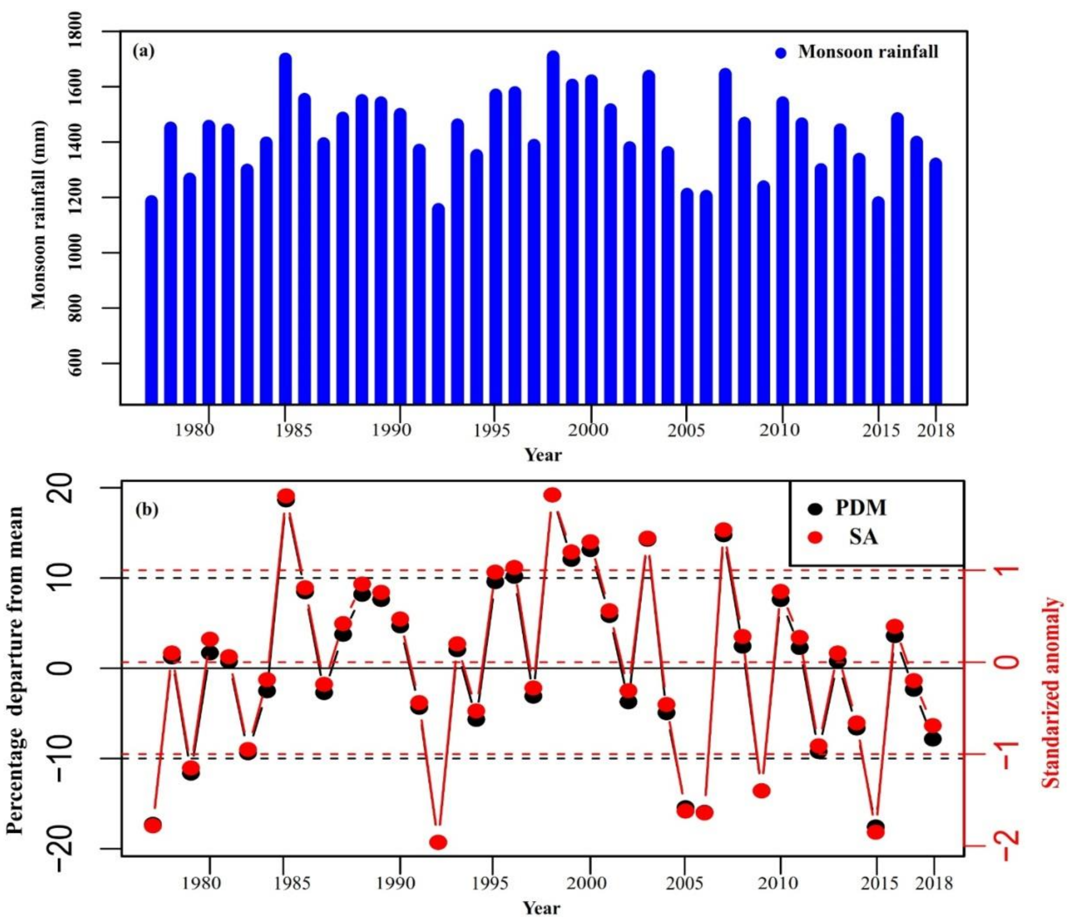

Figure 3: Temporal variability of (a) monsoon rainfall and (b**)** % departure from the mean (monsoon anomalies) left side and standardized anomalies right side from 1977 to 2018.

Rainfall deficits and surplus are defined by the percentage departure or anomaly from the long-term mean. If the summer (June-September) precipitation departure is less than -10%, it is a dry season; less than -15% is a severe dry. If the departure is more than 10%, it is a wet season; more than 15% is a severe wet.

Alternatively, the dry and wet monsoon seasons are marked out by choosing seasons with a standardized anomaly greater than 1 representing wet seasons and those with a standardized anomaly less than 1 dry season of the respective years. Seven large excess (flood) and large deficit episodes in 1984, 1996, 1998, 1999, 2000, 2003, 2007, and (1977, 1979, 1992, 2005, 2006, 2009, 2015) were identified during the study period. The rainfall fluctuation ranges from about 19.29 % below the mean in 1992 and above 19.21 % in 1984 clearly shown in Figure 3b. The average monsoon rainfall is 1433.42 mm. The total amount of rainfall in each large excess episode is provided in Table 1.

Table 1: The rainfall (mm) variability observed in the large excess monsoon rainfall years.

Years	1984	1996	1998	1999	2000	2003	2007
Rank	1	7	2	6	5	4	3
Rainfall in year	1708.44	1579.14	1700.48	1606.19	1621.63	1637.89	1645.13
Excess rainfall above from long-term average	290.02	145.72	267.06	172.77	188.21	204.47	211.71
Percent departure	19.21	10.19	18.65	12.07	13.15	14.29	14.79

In 1984, the summer episode collected 1708.44 mm of rainfall above 290.02 mm from long-term climatology. The remaining large excess monsoon episodes of excess rainfall are presented (Table 1).

Relationship between Monsoon Rainfall and SOI

A comparison of the SOI and the Nepal summer monsoon series reveals (Figure 4) how well these records coincide. The correlation coefficient (CC) between them is 0.52 from 1977 to 2018 at a 95 % confidence level.

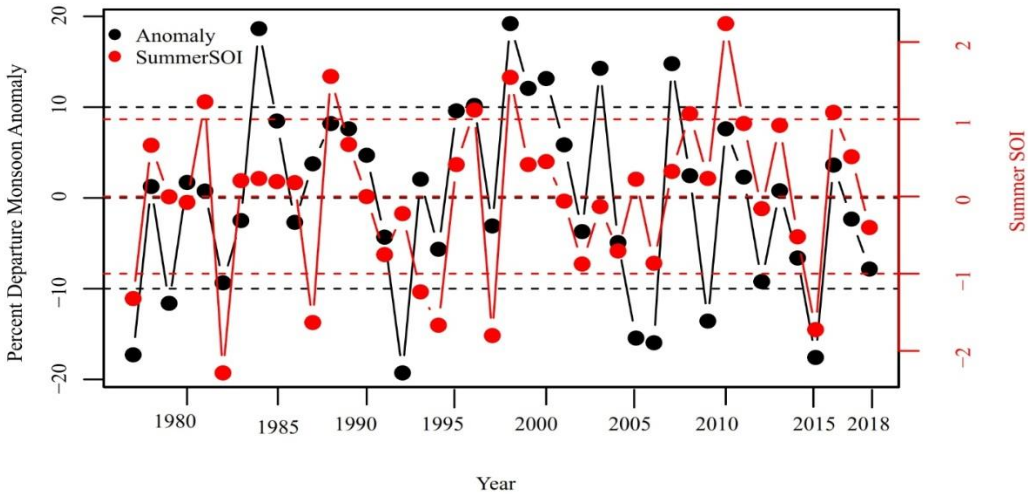

Figure 4: Relationship between percent departure from mean monsoon anomaly and summer SOI.

La Nina years are 1985, 1988, 1989, 1995, 1998, 1999, 2000, 2007, 2008, 2010, 2011, 2016 extracted from https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml. According to this research, Nepal's large excess monsoon (flood) years (1984, 1996, 1998, 1999, 2000, 2003, and 2007) associated with La Nina and normal are extremely wet. This study observed seven large excess (flood) years, only four flood years associated with La Nina years (1998, 1999, 2000, and 2007), and three flood years (1984, 1996, and 2003) are recorded in normal years. So, on a normal and La Nina year, Nepal experienced a significant surplus monsoon (flood) year. The study also quantifies the rainfall during La Nina years, showing that the rainfall anomalies and excess rainfall above average monsoon levels (from 1977 to 2018) are significant. The excess rainfall during La Nina years was approximately 9.07 percent higher than the average monsoon rainfall (1977 to 2018). It was observed that seven large excess (flood) years occurred: four of these were during La Nina years (1998, 1999, 2000, and 2007), while the other three (1984, 1996, and 2003) were in normal years. Both La Nina and normal years resulted in significant surplus monsoon (flood) years for Nepal. Additionally, these flood years are linked to sea surface temperatures in the 3.4 regions from NOAA, with years showing an SST anomaly of less than 0.5°C classified as La Nina years. The research concluded that Nepal experiences both high flood years and normal years associated with La Nina. The average excess monsoon rainfall during La Nina years is about 7.12 percent when the SOI is in its high phase (greater than 0.5).

The present study takes the monsoon seasons' excess years to identify the excess monsoon season rainfall distributions over Nepal. The picture of the rainfall conditions over Nepal in each large excess monsoon season with an interpolated isohyetal map in Figures 5a-f.

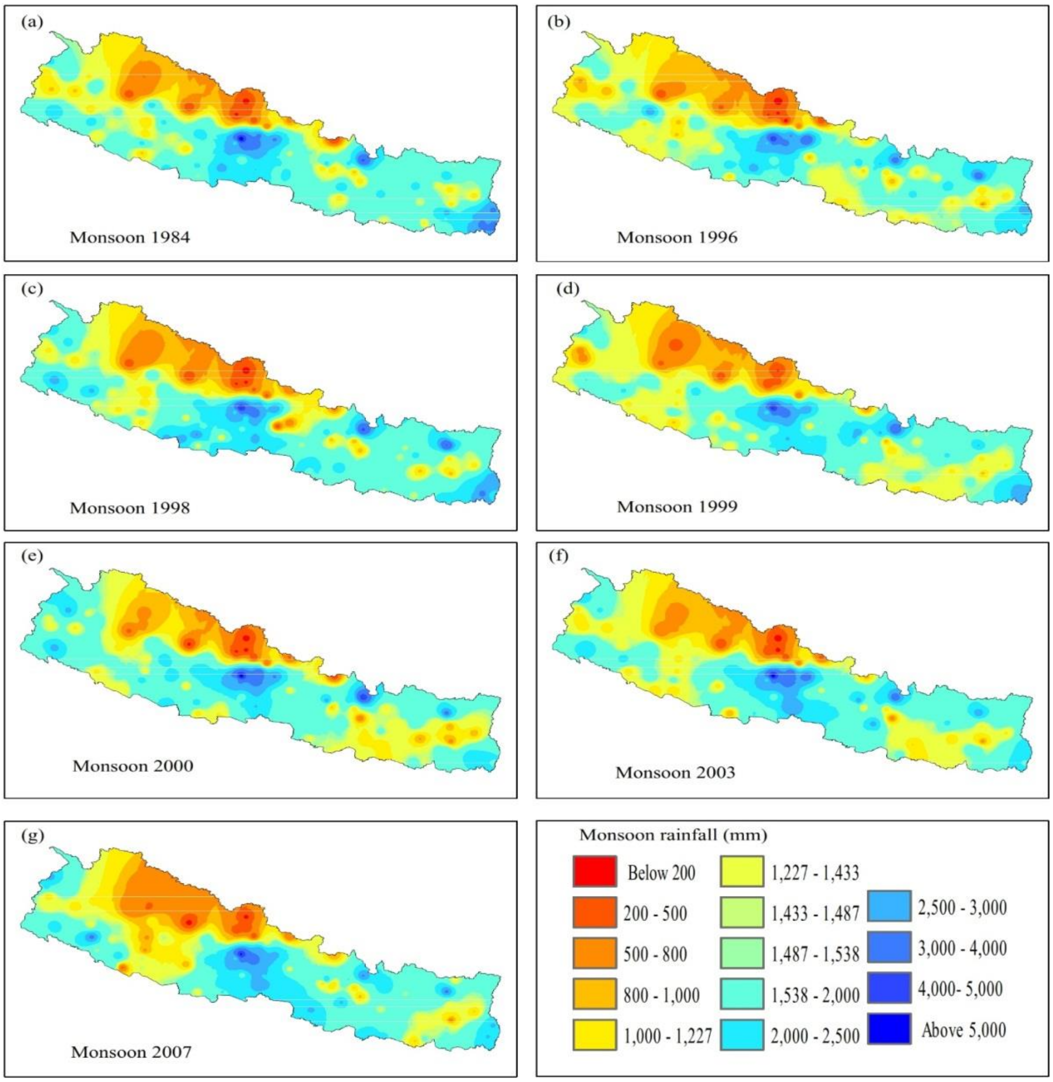

Figure 5: Spatial distributions of monsoon rainfall in large excess years: (a) rainfall 1984, (b) rainfall 1996, (c) rainfall 1998, (d) rainfall 1999, (e rainfall 2000, (f) rainfall 2003, and (g) rainfall 2007.

This study clearly shows the spatial rainfall variability over Nepal in each episode. Strong La Nina episodes develop into stronger monsoons and excess rainfall in Nepal. The seven major excess monsoon cases' pockets of rainfall and dry areas are depicted in the interpolated Figures 5(a-f). The lowest rainfall was received in North north-south region, Figures 5(a-f) clearly show spatial variation of monsoon rainfall. The eastern and central regions recorded excess rainfall during the monsoon rainfall in 1984, whereas the western region recorded a deficiency of rainfall. Similar to this, the center region had greater effects from significant excess monsoon rainfall in 1996 and 2003 compared to the western regions. The central region saw more intense rainfall anomalies in 1998 and 1999 compared to the eastern and western regions. However, the eastern area was more impacted by excessive rainfall in 2000 and 2007 (Figures 5e, g). Overall, both in La Nina as well as normal excess years had a greater impact on central portions of Nepal. Furthermore, after 2007 the rainfall is frequently lower than normal rainfall [Figures (3a, b), and 4].

Composite of large excess years

We examined the combined occurrences of large excess years in Nepal; these years, which included summertime major excess monsoons (floods), are 1984, 1996, 1998, 1999, 2000, 2003, and 2007. There are five composite significant deficit instances in the mean anomaly sets. Thus, the average is the composite of the five significant deficit instances.

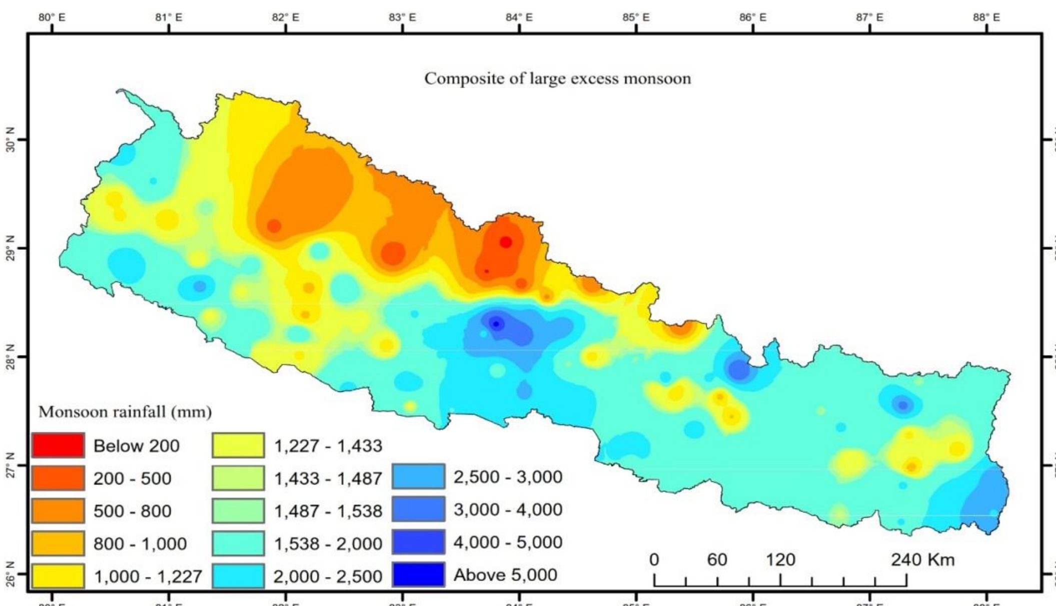

Figure 6: The composite large excess monsoon year's spatial distributions of rainfall.

Figure 6 illustrates the spatial distribution of average monsoonal rainfall during composite large excess years. The central and eastern regions, particularly the mid-mountainous range, experienced heavy rainfall, with totals exceeding 5000 mm. In contrast, the western and northern high mountain regions saw significantly lower rainfall. Areas like Mustang, Manang, Dunai, and Jumla stations in the western and central highlands faced a shortfall, receiving less precipitation than the average monsoonal rainfall. This highlights regional variability in rainfall distribution during excess monsoon years.

Discussion

Almost all of the annual rainfall is received within the monsoon season; it is clear that most of the rainfall obtained by monsoon activities resembles the results (Shrestha, 2000). Nepal is flooded with rain in monsoon months and faces scarcity in the remaining months of the year (Karki et al., 2017).

Bagale et al. (2023a) notice that normally rainfall amounts decrease at higher elevations. The spatial and temporal variation of rainfall is highly variable (Ichiyanagi et al., 2007). This study's results are similar to above mention researchers. This study identified the low and high rainfall regions presented in Figures (5a to g). The regions are dominated Indian monsoon system only the magnitude is variable.

The current findings, which demonstrate a substantial association between SOI and monsoon rainfall, are supported by the study of earlier studies (Sigdel and Ikeda, 2012; Shrestha, 2000). At a 95% confidence level, the correlation coefficient in this study between NSMR and SOI is 0.52. Similar outcomes were reported by Varikoedal et al. (2015) in India, Sien et al. (2015) in Myanmar, and Choudhary (2003) in Bangladesh.

Large monsoon excess events are extreme in La Nina and normal years, according to the current study. Only four (1998, 1999, 2000, and 2007) of the seven significant surplus monsoon (flood) episodes in normal years and three of the seven flood episodes (1984, 1996, and 2003) are linked to La Nina years. On a normal and La Nina year, Nepal experienced a significant surplus monsoon (flood) year. The results of this study's analysis of major excess events during the monsoon season are consistent with those of other studies, including Bagale et al., 2021. Additionally, in India Balme and Jadhav (1984) presented a similar finding, where excess rainfall is documented in normal and La Nina years; aside from the aforementioned La Nina experiences, there have been excess monsoons across India (Varikoden et al., 2015). Strong trade winds cause cooler waters to surface in the east during La Niña by pushing warm water to the western Pacific. This cooling causes weather disruptions, such as increased rainfall and floods in South Asia (Wang et al., 2020).

The western region of Nepal experienced less rainfall than the eastern and central regions throughout the seven major monsoon excess years Figures (5a to g). Large rainfall variability has been observed in Nepal because of the nature of the topography of the lands, leeward, and windward wind directions. Years with significant monsoon excess have been similar to those (Shrestha et al., 2000; Shrestha 2000). Furthermore, some previous studies have noticed the variability of Indian monsoon rainfall linked to El Nino and La Nina occurrences throughout South Asian countries (Varikoedal et al., 2015; Kumar et al., 2013). The results of those investigations support the frequent excess incidents found as presented in the study.

Conclusion

The study analyzed monsoon rainfall variability in Nepal over the past four decades, focusing on percent departures from the long-term average. The average monsoon rainfall is 1433.42 mm, with 17% of years experiencing floods and 17% droughts. Seven years, including 1984, 1996, 1998, 1999, 2000, 2003, and 2007, had significant excess rainfall, exceeding the average by 10-19%. Strong correlations were found between the SOI and monsoon rainfall, especially during excess years. Large excess rainfall occurred in both La Niña and normal years, with four flood years linked to La Niña, where rainfall exceeded the average by 9.07%. The analysis also revealed large spatial variations in rainfall during flood years were unique episodes influenced by large-scale circulations.

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