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Research Article

INFLUENCE OF SOUTHERN OSCILLATION INDEX ON RAINFALL VARIABILITY IN NEPAL DURING LARGE DEFICIENT MONSOON YEARS

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ABSTRACT

The study was conducted using rainfall time-series data for 42 years from 1977 to 2018.We have identified seven large monsoon deficient years. Among these years, 1992, 2009, and 2015 consisted of El Niño episodes which quantify significant rainfall deficits 19.29, 13.6, and 17.59 % respectively from an average rainfall. With some exceptions, all El Niño years observed deficit rainfall. On El Niño years averaged deficit rainfall was approximately nine percent below than the average monsoon rainfall. The eastern region observed the large deficient monsoon years frequently than the central and western regions of Nepal. The central region recorded large spatial variability of average summer rainfall ranging from less than 200 mm/months in lesser Himalayans to more than 3,000 mm/months in mid-mountainous region. The western region had observed a large deficient summer monsoon anomaly 45 % in the year 1979. Similarly, the central region had 31 % deficient summer monsoon anomalies in 1992, and the eastern region observed 25 % deficient anomalies in 1982. There was a strong correlation between the Nepal Summer Monsoon Rainfall (NSMR) and Southern Oscillation Index (SOI). Generally, large negative/positive magnitude of SOI on the Indian and Pacific Ocean has link to weakening/strengthening NSMR.

Keywords: Anomalies, deficit monsoon years, El Niño, Nepal

INTRODUCTION

The Asian monsoon circulation system of the annual cycle has been divided into two different wet and dry phases, which undergo a periodic and high amplitude variation on intra-seasonal, annual and inter-annual timescales (Webster *et al.*, 1998). The active and break period of the monsoon is characterized by precipitation maxima and minima over South-Asia (Ramanadham *et al.*, 1973). The atmosphere is highly complex, and it cannot be expected that the Southern Oscillation could account for most of the monsoon variability (Bhalme and Jadhav, 1984). Although large positive/negative value of SOI signifying strengthening/weakening of the Walker circulation coincides with a large excess/deficient monsoon rainfall in India (Rasmusson and Carpenter, 1983; Bhalme and Jadhav, 1984). Generally, there is a good correlation between a large negative/positive value of SOI and droughts/floods in India, however, there are some exceptions unexplained by the SOI (Mooley and Parthasarathy, 1983; Bhalme and Jadhav, 1984). The Southern Oscillation has an irregular period, ranging from 2 to 6 years, usually averaging between 2 and 3 years (Wright, 1975; Trenberth, 1976; Fredriksen *et al.*, 2020). During the El Niño year in India there is a strong tendency for a below-normal Indian monsoon rainfall over most parts of India (Sikka, 1980; Varikoden *et al.*, 2015; Bhalme and Jadhav, 1984). Similarly, during the El Niño/La Nina phenomena there is a good correlation between a large negative/positive value of SOI and droughts/floods in Nepal (Shrestha *et al.*, 2000; Sigdel and Ikeda, 2012). El Niño Southern Oscillation (ENSO) develops the weaker monsoon rainfall in South Asian countries Nepal, India, Bangladesh, and Sri Lanka described in detail by the researchers (Shrestha *et al.*, 2000; Varikoden *et al.*, 2015; Chowdhury, 2003; Silva and Hornberger, 2019). The effect of ENSO and Indian Ocean Dipole (IOD) events on the rainfall variability is still undefined and unclear (Muangsong *et al.*, 2014; Cherchi and Navar, 2013).The influence of SOI on monsoon rainfall over Myanmar was significant than the linkage with IOD (Sien *et al.*, 2015). Similarly, the influence of SOI on monsoon rainfall over Nepal was more significant than the effect of IOD (Sigdel and Ikeda, 2012). Shrestha, (2000) identified that there is a strong correlation between SOI and summer rainfall over Nepal. Strong El Niño episodes develop to weaker monsoons and droughts in South Asian region (Fan *et al.*, 2017). El Niño characterized by warming of surface temperatures in the Pacific Ocean, is associated with lower than normal monsoon rainfall in the South Asian region (Varikoden and Babu, 2015; Wang *et al.*, 2020).

The record of the annual cycle of the monsoon system shows that most of the rainfall occur from June to September as the southwest Indian monsoon enters Nepal. Southeasterly circulation brings abundant rainfall (moisture) from the Bay of Bengal and occasionally from the Arabian Sea (Bohlinger *et al.*, 2017). The winter season is dominated by westerly circulation originating from the Mediterranean Sea and Siberia (Kanskar *et al.*, 2004). The influence of these two circulation systems is heterogeneously distributed over Nepal; summer rainfall greater in the central and eastern regions cause southeasterly and westerly derived winter rainfall most significant in the western region of Nepal (Kanskar *et al.*, 2004). Moreover, Wang *et al.* (2013) studied the drought over the western region of Nepal to investigate the winter deficit rainfall. Rainfall is the only primary source of both surface and groundwater in Nepal. It is essential to understand large-scale atmospheric circulation system connections to monsoonal variability over Nepal from a socioeconomic aspect, such as drought risk, flood damage, effect on hydropower generation, and crop production practices.

Many studies had concentrated on rainfall variability in Nepal, (Kanskar *et al.*, 2004; Ichiyanagi *et al.*, 2007; Salerno *et al.*, 2015; Karki *et al.*, 2017; Shrestha *et al.*, 2019; Sigdel and Ma, 2017; Pokharel *et al.*, 2020). However, few authors have researched monsoon rainfall connecting with large-scale atmospheric circulation (Shrestha *et al.*, 2000; Sigdel and Ikeda, 2012; Sharma *et al.*, 2020). Shrestha *et al.* (2000) identified that strong El Niño episodes develop to weaker monsoons and deficit rainfall in Nepal. Sigdel and Ikeda, (2012) concluded main large-scale pattern influential on the monsoon rainfall variability was explained by ENSO as a significant correlation with SOI. Sharma *et al.* (2020) identified the year-to-year dominant variability of summer rainfall in Nepal which corresponds with ENSO. However, there is still a gap in identifying the large deficient monsoon years and its spatial variability relating with SOI across the country.

The main objective of this research is to investigate the large monsoon deficient years associated with El Niño and normal years during the last 42 years (1977-2018). Similarly, this research focused on rainfall variability in the western, central, and eastern regions during the monsoon period.

MATERIALS AND METHODS

Study Area

Nepal is a landlocked mountainous country situated in the central Himalayas of South Asian territory. The northern side is situated in Highland Tibet of China, and the remaining sides surround India. It extends from 80° 04' to 88° 12' E in longitude and 26° 22'to 30° 27' N in latitude (Sigdel and Ikeda, 2010). The country extends 885 km from east to west, varies from 130 km to 260 km in the North to the south (Karki *et al.*, 2017), and covers 147516 sq. km (Shrestha *et al.*, 2020).The complex topography of Nepal ranges from the low land of Terai 60 meters in south to Mount Everest 8848.86 m above sea level in the Himalayan region towards the North. The climate of Nepal is sub-tropical, with most of the rainfall concentrated in the monsoon season (Karki *et al.*, 2015). We have further classified the country into the western, central, and eastern regions to identify the differences of the spatial variations of NSMR.

Data and Methods

Data (Methods of Data Collection)

The daily rainfall data of 107 weather stations acquired from the Department of Hydrology and Meteorology, Government of Nepal. Monthly total rainfall values were obtained by summing up daily rainfall data. Similarly, the annual total rainfall data were calculated by adding monthly total rainfall data from January to December, and for summer monsoon (June–September), total annual rainfall at each station was computed after completing the missing data. The distribution of the meteorological stations is shown in Fig.1. Available observed rainfall data covering the year between 1977 to 2018. Time range was determined by evaluating the records of the stations as possible as more stations. Annual, seasonal, and monthly means were calculated for all stations using the arithmetic mean method. The annual mean is averaged over January-December. After data collection and study of climate datasets, stations were selected based on less than 10 % missing records, and most of the stations (95 %) were lower than 3 % of the total number of annual values. Some high-altitude stations are used for spatial coverage having 30 years' time series with 5-10 % missing values. We have adopted the Normal ratio method to estimate missing rainfall values of climate datasets from nearby three weather stations (Myrondis, D & Nikolaos, T., 2021, Bagale *et al.*, 2021). Monsoon rainfall was interpolated and visualized by using inverse distance weighted (IDW) technique (Patel *et al.*, 2007).

The SOI is one measure of the large-scale fluctuations in air pressure observed between the western and eastern tropical Pacific during El Niño and La Niña episodes (Yan *et al.*, 2011).The negative phase of the SOI represents below-normal air pressure at Tahiti and above-normal air pressure at Darwin. Monthly Southern Oscillation Index (SOI) data and Ocean Nino Index (ONI) monthly sea surface temperature (SST) anomaly over the Nino-3.4 regions were acquired from the National Weather Service Climate Prediction Centre of National Oceanic and Atmospheric Administration (NOAA) available on https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml, accessed 5 January 2020 for the time 1977 to 2018. The ONI defined by three months running mean SST anomalies in the Nino-3.4 regions, which is also known as the Nino-3.4 index.

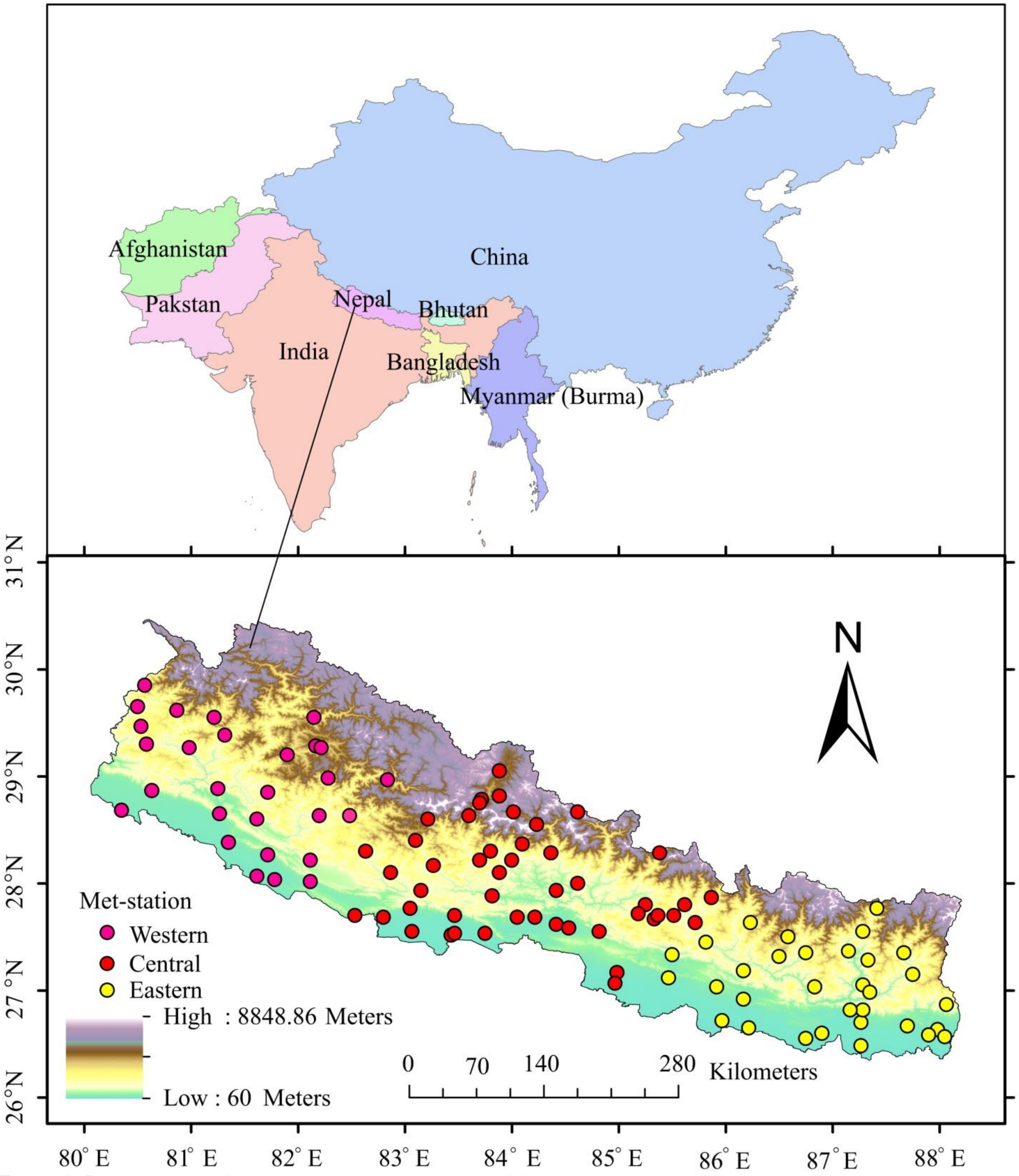

Figure 1. Location map of the study area along with rainfall stations used in this study; pink, red and yellow color respectively represents the stations for the western, central, and eastern regions between 1977 and 2018.

Methodology for Identification Departure of Deficit and Excess Years

Bhalme and Jadhav (1984) and Varikoden *et al.* (2015) used the ±10 % departure from long-term mean to excess /deficit Indian Summer Monsoon Rainfall climatology was identified as severe flood/drought years in India. Flood/Drought document in Nepal using anomalies is limited; it is new; this study used ± 10 % departure from long term mean monsoonal rainfall to identify the severe extreme events. Percent Departure Nepal Summer Monsoon Rainfall (PDNSMRi) is easily calculated.

$$PDNSMR_i = \frac{R_i - \bar{R}}{\bar{R}} * 100\ \%$$

Where R_i and $\bar{R}$ denote all Nepal summer monsoon rainfall and means all Nepal monsoon rainfall for 42 years datasets, the Percent Departure Summer Monsoon Rainfall of each 107 stations was calculated the same.

The Student's t test is used to check statistically significant test for monsoon rainfall anomalies. Furthermore, Gumus and Algin, (2017) defined stations proportion is the number of stations relative to the total number of stations used.

The El Niño years were identified based on the three-month running average SST anomalies over the Nino-3.4 regions. We considered a year as El Niño when the value of Nino 3.4 SST anomaly is greater than 0.5 degree Celsius and a year as La Niña when the value of Nino 3.4 SST anomaly is lower than 0.5 degree Celsius in any five consecutive overlapping months. The detail information of El Niño episodes was obtained from NOAA (Website) URL, https:/origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml.

RESULTS

Rainfall Statistics

The monthly rainfall statics of 1977 to 2018 revealed that the precipitation strongly increased from May (7 %), with the highest in July (27 %) due to the influence of summer monsoon while the lowest recorded in November (Fig. 2a) below 1 %. Approximately 50 % of the annual rainfall was recorded during July and August in two months, and 80 % of the annual rainfall occurs, during the monsoon season, followed by the pre-monsoon 13 %, post-monsoon 4 %, and winters 3 %. Monsoon rainfall variability with respective year to year varied from 74 % in 1992 to 86 % in 1984 (Fig. 2b).

Table 1. Regional rainfall (mm) statistics

Region	Western	Central	Eastern
Winter	91.40	61.46	40.28
Pre-monsoon	171.41	229.42	281.94
Monsoon	1239.36	1515.31	1491.19
Post-monsoon	51.50	74.92	98.12
Annual	1553.68	1881.11	1911.53

Summer rainfall observed greater in the central region with comparisons to the eastern and western regions of Nepal. However, the western region observed low annual rainfall but high amount of Westerly derived winter rainfall in winter season than other regions of Nepal (Table 1). Pre- and post-monsoon rainfall increases from the western to eastern Nepal. Though, the annual rainfall decreases from eastern to western Nepal.

Monsoon Rainfall

During the 42 years the mean monsoon rainfall is 1,433.2 mm/month. Monsoon rainfall widely varies over different parts of the country with lowest over Northwest part (< 200 mm) and highest over central mid-mountainous part (> 3000 mm) of the country followed by Northeast part. The spatial variations of monsoon rainfall have clearly observed the dry areas as well as wet areas in different regions over the country in the isohyetal map. Low rainfall observed in Mustang region lies on lesser Himalayans and high in Lumle region lies on the mountainous region of central Nepal (Fig. 3).

Generally, the amount of mean monsoon rainfall observed decreases from the east to west region. However, in the central region of Nepal there are certain pockets with heavy monsoon rainfall totals.

Temporal Variability of Monsoon Anomaly in Nepal

We have used an average rainfall of 107 stations for the monsoon anomaly (Fig. 3). Excess/deficit years were identified based on the percent departure of NSMR (anomalies). Anomalies are prepared based on climatology for the period 1977–2018. A season is defined as a large excess (flood)/ large deficient (drought) season when the departure percent is ±10 % from the mean NSMR. From this statistical analysis the seven flood/drought years were 1984, 1996, 1998, 1999, 2000, 2003, 2007 and 1977, 1979, 1992, 2005, 2006, 2009, 2015 respectively. The rainfall anomalies observed below the mean is 19 seasons and above is 23 seasons.

The deficit fluctuation of rainfall anomalies was about 19.29 % in 1992 and followed 2015 at about 17.59 %. Similarly, the excess fluctuation of rainfall anomalies was 19.21 % in 1998 and followed 2007 at about 14.79 % (Fig. 4). Furthermore, the deficit and excess monsoon anomalies and rainfall are clearly depicted in Table S1.

Regional Temporal Variations of Monsoon Rainfall

We used average rainfall of 28 stations for the western region, 47 stations for the central region and 32 stations for the eastern region to show the temporal variability of rainfall in respective regions as depicted in Fig. 5a. The regional rainfall shows that the eastern and central regions of Nepal observed more rainfall than the western region.

During the study periods, 25 seasons of high rainfall were observed in the central region compared with the eastern region, and 17 seasons observed more rainfall in eastern Nepal. However, in recent years the rainfall has been decreasing in the eastern region compared to the central region. In all 42 years, the western region of Nepal observed low rainfall than the central and eastern regions of Nepal except in 2013. The rainfall record (Fig. 5a) shows the decreasing and increasing rainfall characteristics in the western, central, and eastern regions. The average monsoon rainfall totals in the central region of Nepal observed more than eastern and western regions (Table 1).

The variability of an anomaly of the western, central, and eastern regions is in different characteristics each year. For example, the large deficient monsoon (drought) year percent departure of rainfall in the western region was about -45 % in 1979. Similarly, in the central region, the large deficient monsoon year percent departure of monsoon rainfall was 31.37 % in 1992, and in the eastern region about 25.27 % percent departure monsoon rainfall was in 1982. The decreases of anomalies (percent departure monsoon rainfall) in these regions on deficit rainfall years are shown in Fig. 5b.

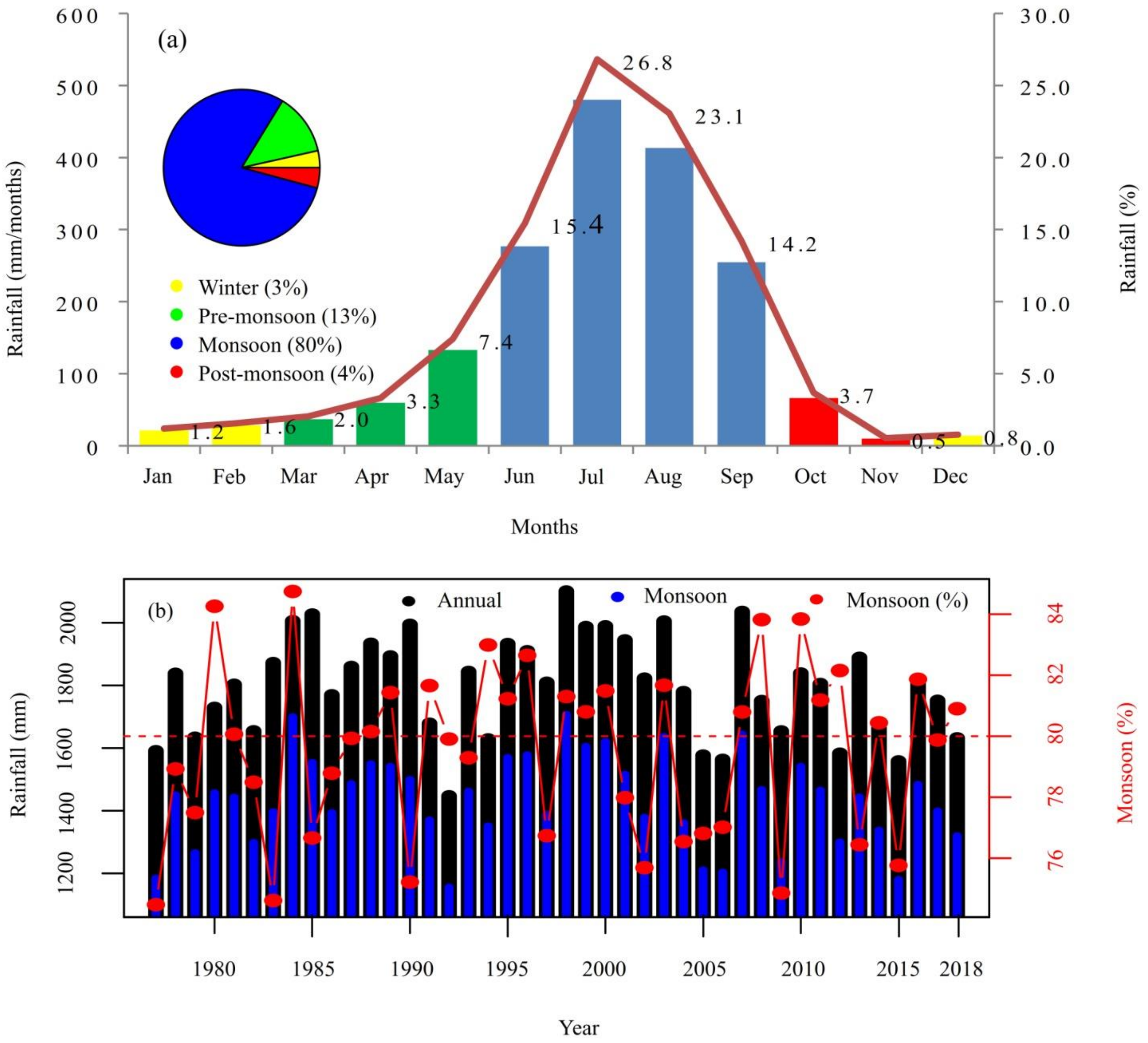

Figure 2. Variability of (a) Monthly rainfall statistics averaged from 1977 to 2018 and Pie chart shows the seasonal amount of rainfall (%). (b) annual monsoon rainfall variability and percent monsoon rainfall for the period 1977-2018

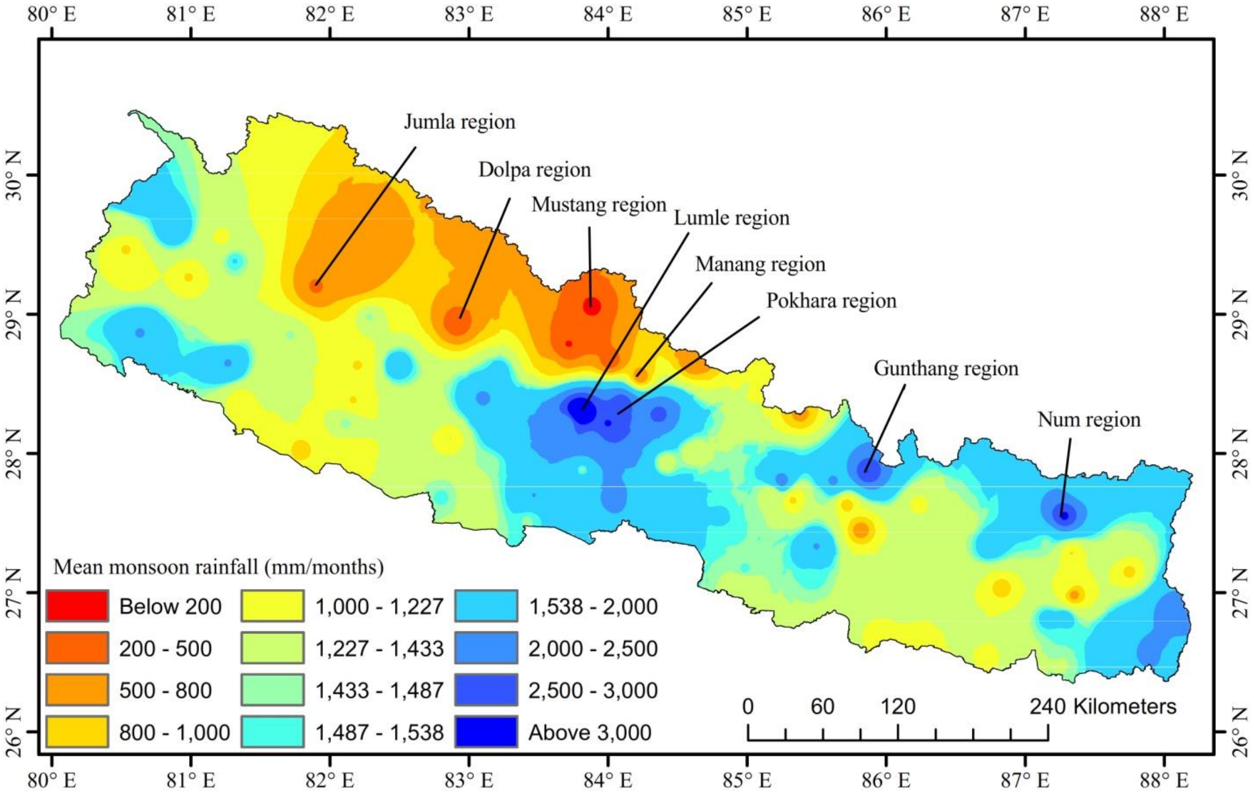

Figure 3. Spatial distributions of mean Monsoon rainfall over Nepal from 1977 to 2018

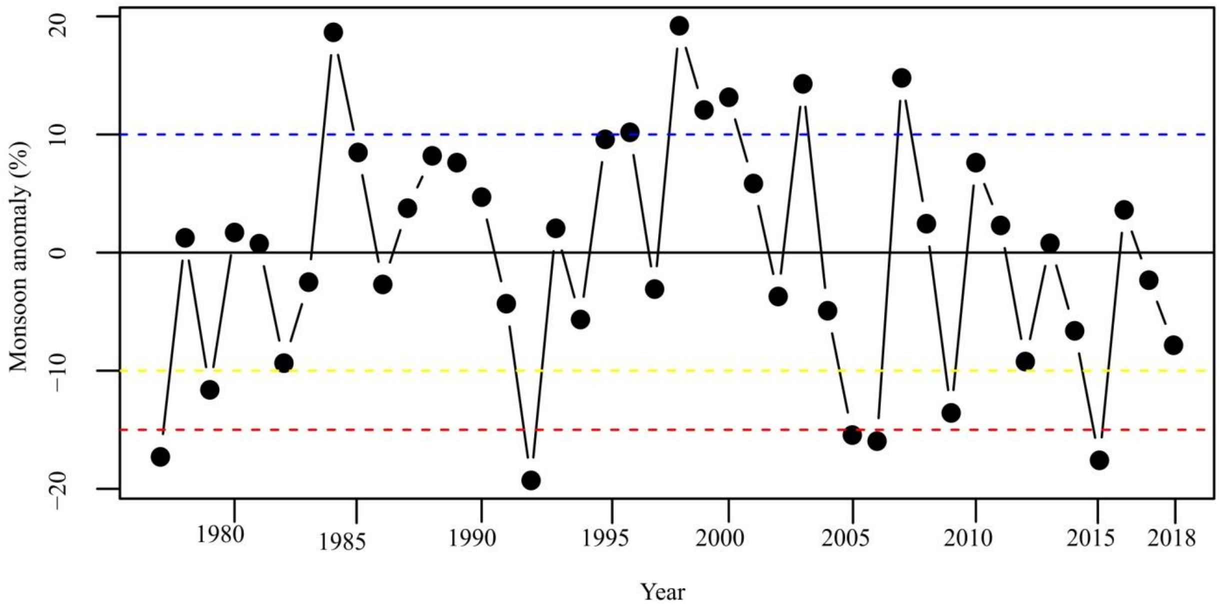

Figure 4. Temporal Variability of Monsoon Anomalies from 1977 to 2018

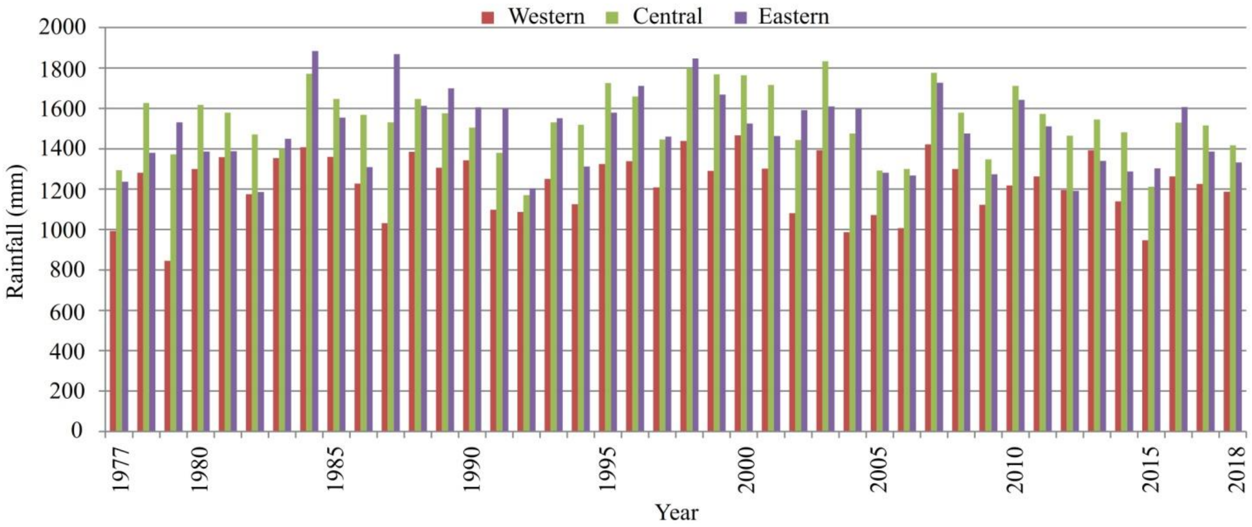

Figure 5a. Temporal Variability of Regional Monsoon Rainfall from 1977 to 2018

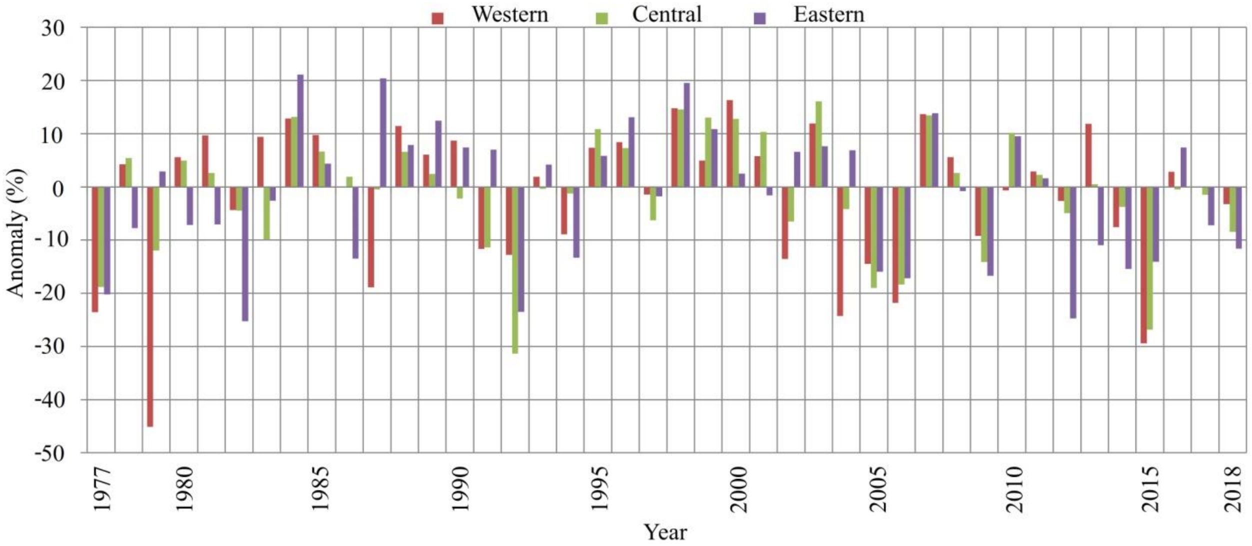

Figure 5b. Temporal Variability of Regional Monsoon Anomalies from 1977 to 2018

The western, central, and eastern regions of Nepal recorded ten, seven, and thirteen seasons of large deficient monsoon (drought) years respectively. The regional deficient monsoon years and its rank are shown in Table 2. Moreover, the western region of Nepal recorded seven seasons of large excess monsoon (flood) years in recent 42 years. The flood years were 2000, 1998, 2007, 1984, 2003, 2013, and 1988. Similarly, the central region recorded nine seasons of large excess monsoon (flood) years. The flood years are 2003, 1998, 2007, 1984, 1989, 2000, 1995, 2001, and 2010. While in the eastern region recorded 7 seasons as large excess monsoon (flood) years. The flood years are 1984, 1987, 1998, 2007, 1996, 1989, and 1999. Comparing the results region-wise, the eastern region of Nepal faced more dry conditions frequently than the central and western regions of Nepal are shown in Table 2.

Relative Frequency of Monsoon Rainfall in Large Deficient Monsoon Episodes

This study quantifies the seven large deficient monsoon year's stations proportion expressed in percent which are depicted in table 3 and we also present large deficient year's deficit rainfall in each drought episodes from long term average. Spatial extents of the variability of rainfall are interpolated over Nepal in Fig. 6 (a-g).

Table 2. Regional Large Deficit Percent Departure Monsoon Rainfall in Nepal from 1977 to 2018

Rank	Eastern			Western			Central		
	year	Monsoon Rainfall mm	Percent departure	year	Monsoon Rainfall mm	Percent departure	year	Monsoon Rainfall mm	Percent departure
1	1982	1186.70	-25.3	1979	845.37	-45.1	1992	1170.61	-31.4
2	2012	1191.80	-24.7	2015	947.73	-29.4	2015	1212.20	-26.9
3	1992	1203.68	-23.5	2004	987.13	-24.3	2005	1292.27	-19.0
4	1977	1236.39	-20.2	1977	992.66	-23.6	1977	1293.97	-18.8
5	2006	1268.35	-17.2	2006	1006.98	-21.8	2006	1299.30	-18.4
6	2009	1273.35	-16.7	1987	1031.64	-18.9	2009	1347.04	-14.2
7	2005	1282.04	-16.0	2005	1071.61	-14.5	1979	1373.19	-12.0
8	2014	1288.21	-15.4	2002	1080.41	-13.5	1991	1380.82	-11.4
9	2015	1302.82	-14.1	1992	1087.77	-12.8			
10	1986	1309.75	-13.5	1991	1098.22	-11.7			
11	1994	1311.76	-13.3						
12	2018	1331.78	-11.6						
13	2013	1339.59	-11.0						

Table 3. Large deficient monsoon rainfall statistics based on stations proportion expressed in percent in different years

Rank	Year	<Average monsoon rainfall mm	<10% monsoon rainfall mm	Deficit rainfall below from long term average (mm)
1	1992	73	66	276.26
2	2015	72	63	251.86
3	1977	72	48	247.72
4	2006	70	65	228.59
5	2005	68	55	221.26
6	2009	66	56	194.37
7	1979	62	51	166.35

Large deficient summer monsoon was in 1992. In this episode 66 % stations observed below 10 % monsoon rainfall anomalies and more than 73 % stations are observed below from mean monsoon rainfall. Large deficit monsoon years ranking from first to seventh is tabulated in Table 3 with rainfall statistics.

Spatial Distribution of Monsoon Rainfall Variability on Large Monsoon Deficit Years

Nepal is a mountainous country with complex topography; Nepal faces the leeward side with low rainfall in the Northern part of Nepal. This area of Nepal is semiarid; low monsoon rainfall areas are Mustang, Dunai and Manang located in the lesser Himalayans regions. These locations recorded < 200 mm in the monsoon season. The spatial distribution of rainfall across Nepal indicates high rainfall or pocket rainfall areas surrounding Lumle, Num, Pokhara, and Gumthan. Lumle and Pokhara lie in the central region of Nepal on High and Mid Mountainous near the Annapurna region. Num and Gumthang lie on the eastern part of high mountain regions record more than 3000 mm/months in the monsoon season. The interpolated Fig. 6(a-g) indicates the pockets rainfall areas as well as dry areas in the seven large deficient monsoon cases.

In the recent four decades, we observed and analyzed the western, central, and eastern regions rainfall statistics. The large monsoon rainfall deficit recorded in 1979 on western region which was 45.09 % from the mean rainfall of the western region. Similarly, the central region and eastern region have recorded large monsoon rainfall deficient in year 1992. In this year, central and eastern regions have measured rainfall anomalies decreases 37.37 % and 23.50 % respectively. In the monsoon drought years 1979, 2015, 1977, and 2006 the western region of Nepal was more affected by large rainfall deficit in comparisons to the central and eastern regions [Fig. 6 (b, c, e and g)]. In these years the mountainous region of the central and western region recorded low rainfall. In the particular year 1979, the eastern region recorded excess rainfall, but the western region recorded a large deficit rainfall during the recent 42 years. While in the central region, rainfall anomaly decreases by 11.99 %, but the eastern region increases rainfall anomaly by 2.92 %. Similarly, in the year 1992 the central region was more affected by a large deficit monsoon rainfall in comparison to eastern and western regions followed by the year 2005. In the year 1992, the central region witnessed a decrease in larger rainfall anomalies than the eastern and western regions (Table 2). But in 2009 the eastern region was more affected by deficit rainfall than any regions of Nepal (Fig. 6f).

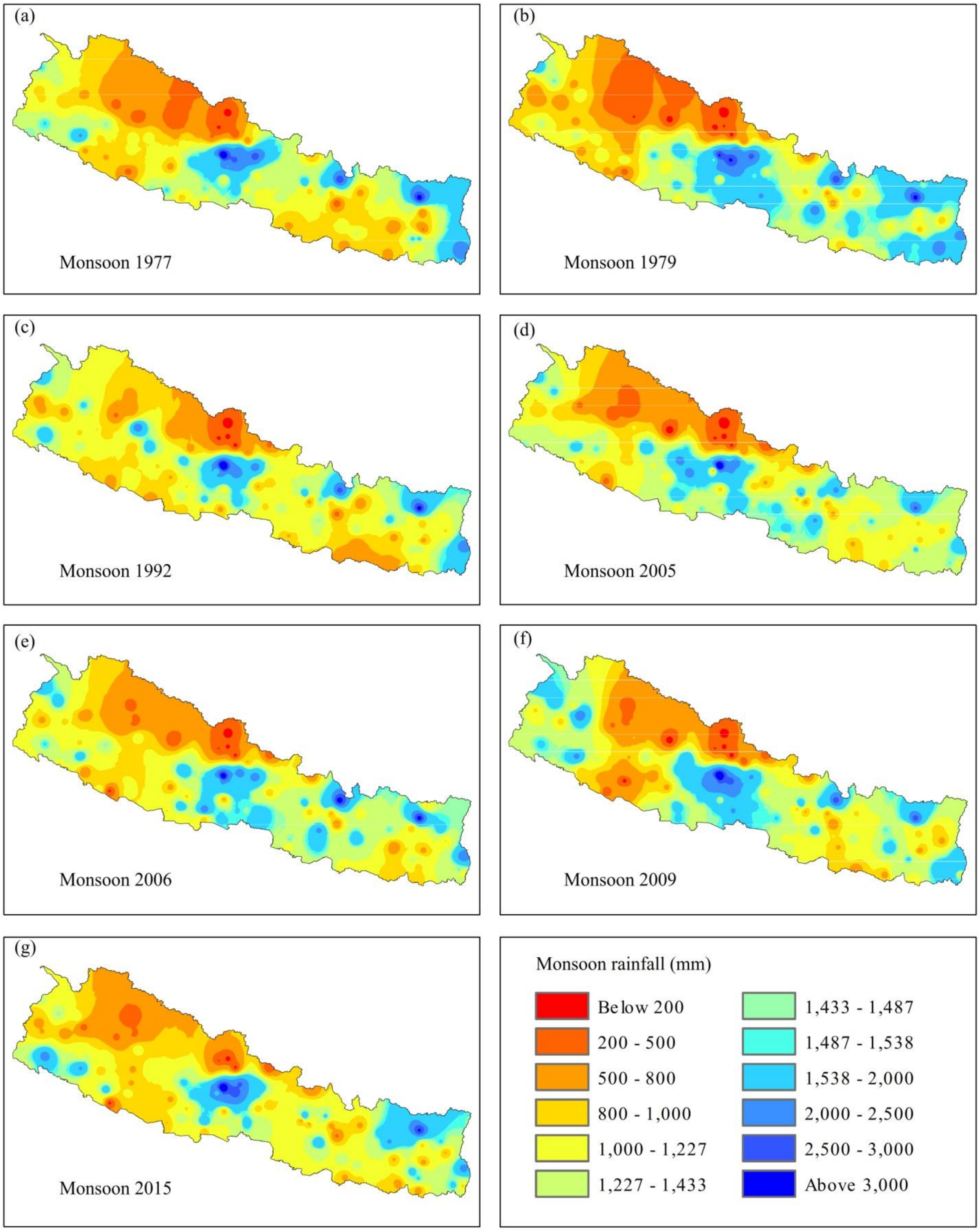

Figure 6. Spatial distributions of (a) monsoon rainfall 1977, (b) monsoon rainfall 1979, (c) monsoon rainfall 1992, (d) monsoon rainfall 2005, (e) monsoon rainfall 2006, (f) monsoon rainfall 2009, and (g) monsoon rainfall 2015

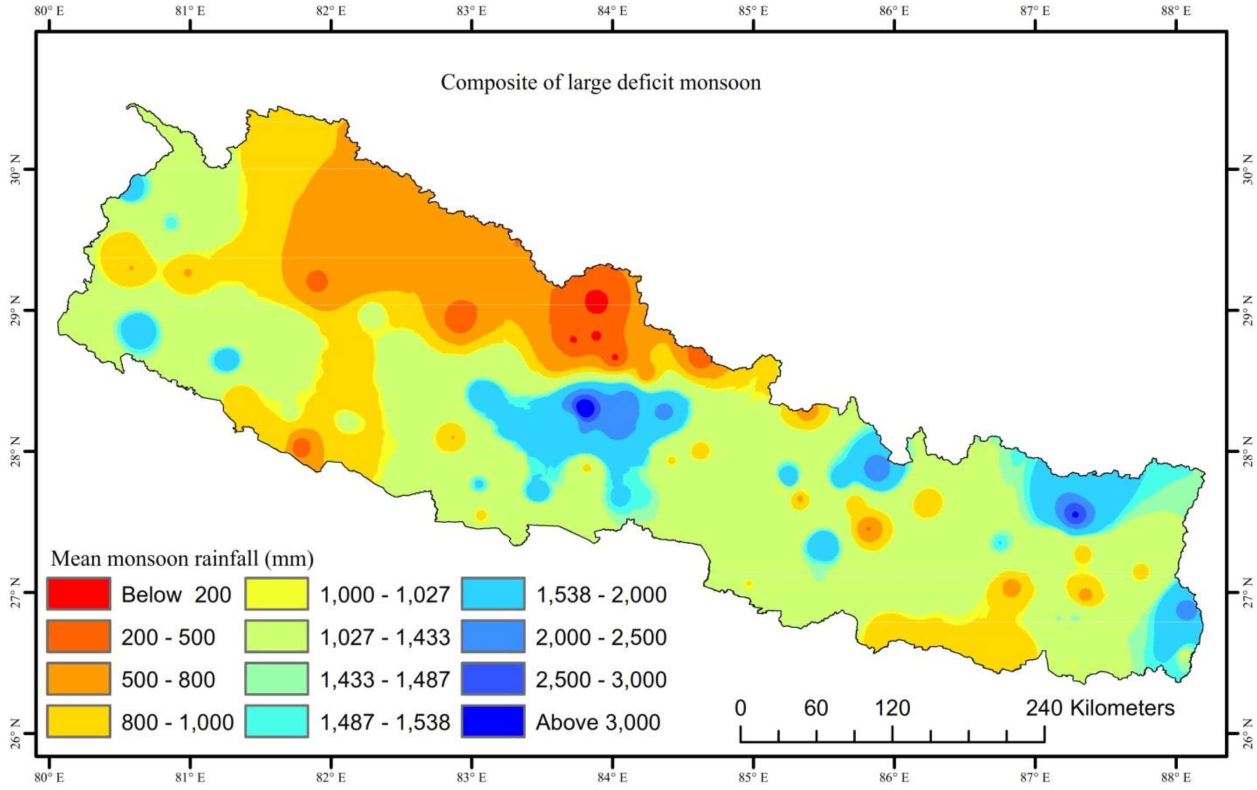

Figure 7. Spatial distributions of composite large deficit monsoon years

Composite of Large Deficit Years

We have analyzed the composite episodes for extreme years over Nepal; consisting of summer large deficient monsoon (drought) years are 1977, 1979, 1992, 2005, 2006, 2009, and 2015. The mean anomaly sets of 5 composite large deficit episodes were less than 15 %. Therefore, the composite of the 5 large deficit episodes is averaged.

The spatial distributions of the mean monsoonal of composite large deficit years are shown in Fig. 7. The central part of Nepal recorded more rainfall which belongs to the high and mid mountains near the Annapurna region. The rainfall pockets area of Nepal recorded > 3000 mm rainfall during the drought years in Lumle, Pokhara, Num, and Gumthang which lie on the mountain regions of central and eastern parts of Nepal. On the other hand, the central and western parts of high lands are facing a rainfall deficit. The deficit areas are in Mustang, Manang, Dunai, and Jumla station recorded low precipitation than mean monsoonal rainfall in composite large deficit years.

Relation between NSMR and SOI

This study used the SOI index, which measures a large-scale fluctuation in sea level pressure between La Nina and El Niño episodes. Comparison between all Nepal summer monsoon series and SOI shows (Fig. 8) the substantial correlation between SOI and NSMR records.

Deficit period with SOI (-), excess period with SOI (+); the NSMR and SOI are 31 (about 74 %) times the phase relation (positive/negative SOI, positive/Negative NSMR (Fig. 8). In 31 times phase relation 14 (about 45.16 %) times deficit and 17(about 54.84 %) times excess summer rainfall in Nepal. The correlation coefficient between NSMR and SOI is 0.52 from 1977 to 2018 at a 95 % confidence level. During the study periods, the average deficit monsoon rainfall is 8.72 percent in the low phase of SOI (< -0.5), while the average excess is 7.12 percent in the high phase of SOI (> 0.5). From the above-mentioned phase relation between NSMR and SOI analysis, the all-Nepal monsoon record series is highly influenced by the SOI. Such a similar pattern is noticed in NSMR in large deficit (drought) years. However, during the drought/flood period SOI and the NSMR are strong (-/+) more than the normal years. The strength/weakness of the monsoon system was identified as La Nina/El Niño years for high NSMR variability. The El Niño years are 1982, 1983, 1987, 1991, 1992, 1997, 1998, 2002, 2004, 2009, 2015, 2016 and La Nina years are 1985, 1988, 1989, 1995, 1998, 1999, 2000, 2007, 2008, 2010, 2011, 2015) during study periods extracted from https://origin.cpc.ncep.noaa.gov/products/precip/CWli nk/MJO/enso.shtml.The years 1998 and 2016 marked both El Niño and La Nina episodes. However, monsoon seasons of Nepal dominated by excess rainfall in these years. Our findings show that Nepal's large deficit monsoon (drought) years associated with El Niño and normal both are extreme dry years. All El Niño years were the deficit, but in year 1987(El Niño) there was excess monsoon rainfall observed in Nepal (Fig. 2b). It is a need to further investigation for the justification causes. Moreover, this study quantifies the El Nino year's rainfall with their decreasing percent rainfall anomalies and deficit rainfall below average monsoon rainfall between 1977 and 2018 in (Table S1 and Table 4).

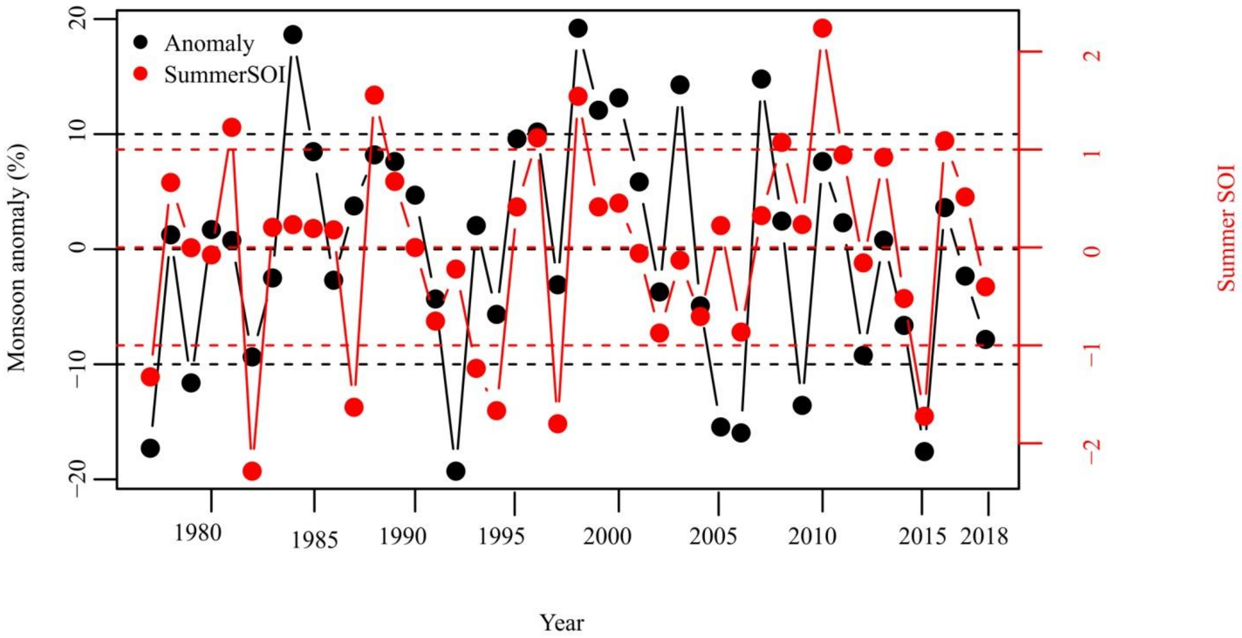

Figure 8. Relationship between Percentage Departure of NSMR and SOI

Table 4. The rainfall variability observed in the large deficit monsoon rainfall years by El Niño events

Years	1982	1983	1991	1992	1997	2002	2004	2009	2015
Deficit rainfall (mm)	134.12	35.83	61.97	276.43	44.27	53.22	70.55	194.53	252.03

In 1992, summer episodes collected 1156.74 mm/months rainfall below 252.03 mm/months than the long-term average. Other large deficient monsoon events rainfall deficits are tabulated in table 4. On El Niño episodes averaged deficit rainfall observed approximately nine percent below from an average monsoon rainfall (1977 to 2018).

During the study period, this study observed seven drought years in Nepal only three years associated with El Niño years, and four drought years are in normal years. The first and second extreme drought in 1992 and 2015 were associated with El Niño years, and the third drought in 1977 occurred in normal year.

DISCUSSION

Approximately 80 % of the annual rainfall is received during the monsoon season (Kanskar *et al.*, 2004; Sigdel and ikeda, 2012; Karki *et al.*, 2017). This study also identified that contributions of monsoon rainfall was 74 % in year 1992 and 86 % in year 1984. The similar results presented by Shrestha *et al.* (2000) identified the year 1992 was the driest during the periods (1948-1994) using 75 stations over Nepal. In that particular year, whole Nepal recorded below normal rainfall which coincided with an El Nino event.

Present study shows that large monsoon deficient episodes are extreme in El Niño and normal years. Out of seven large deficient monsoons (drought) years, only three drought years associated with El Niño years (1992, 2009, and 2015) and four drought years (1977, 1979, 2005, and 2006) are recorded in normal years. The year 1977 is a large deficient monsoon year observed on normal year. So, Nepal observed a large deficient monsoon (drought) year on El Niño and normal year. The findings of monsoon seasons large deficit events from this study are also similar with other studies such as Sharma *et al.*, 2020. Furthermore, A similar result presented by Balme and Jadhav, (1984), in India where drought is recorded in both El Niño year and normal year; however, there have been deficient monsoons over India apart from the mentioned El Niño episodes (Varikoden *et al.*, 2015).

During the seven large monsoons deficient years' western regions of Nepal recorded comparatively low rainfall than eastern and central regions. In the year 1979, 1992, and 2015 the central region recorded low monsoon rainfall than the eastern region, and in the year 1977, 2005, 2006, 2009, the eastern region records low monsoon rainfall (Fig. 5a). The large monsoon deficient years have resembled Shrestha *et al.* (2000) and Shrestha (2000). Furthermore, in the recent decades some researchers (Wang *et al.*, 2019; Varikoedal *et al.*, 2015; Kumar *et al.*, 2013) identified the inter-decadal weakening of the South Asian Summer Monsoon frequently after 2000 both on El Nino and Normal years over the South Asian countries. Those studies support the findings of drought events frequently as reported in the present study.

The previous researchers' (Sigdel and Ikeda, 2012; Shrestha, 2000) findings supports the present results that there a strong correlation between SOI and monsoon rainfall. In this study the correlation coefficient between NSMR and SOI is 0.52 at a 95% confidence level. Similar results were presented by Chudhary *et al.* (2003) in Bangladesh; Sien *et al.* (2015) in Myanmar and Varikoedal *et al.* (2015) in India.

CONCLUSIONS

The study provided concise knowledge about the temporal (all-Nepal as well as regional) and spatial variability of monsoon seasons using a rainfall anomaly over Nepal during the past four decades (1977- 2018). There were seven large deficit monsoon years 1977, 1979, 1992, 2005, 2006, 2009, and 2015 with deficit percent of rainfall 17.30, 11.62, 19.29, 15.45, 15.96, 13.57 and 17.59 respectively from long term average on corresponding monsoon episodes. The eastern region frequently showed the monsoon dry signals compared with the central and western regions. Moreover, whole Nepal indicates that after the year 2000 large deficit rainfall events evolved frequently. The average deficit monsoon rainfall is 8.72 percent in the low phase of SOI (< - 0.5). The correlation coefficient between SOI and NSMR is strong on large deficit monsoon years than normal years, the correlation coefficient between NSMR and SOI is 0.52. Present study showed that large deficient years are observed both in El Niño and normal years. Out of seven drought years, only three years associated with El Niño years. With some exceptions, all El Niño years measured deficit rainfall. Deficit rainfall during the El Niño years observed approximately nine percent below the average monsoon rainfall.

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AUTHOR CONTRIBUTIONS

Damodar Bagale designed the study, data analysis and original draft preparation. Deepak Aryal and Madan Sigdel prepared the paper with significant input.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

REFERENCES

Bagale, D., Sigdel, M., & Aryal, D. (2021). Drought monitoring over Nepal for the last four decades and its connection with southern oscillation index. *Water*, *13*(23), 3411. https://doi.org/10.3390/w13233411

Bhalme, H.N., & Jadhav, S.K. (1984). The Southern Oscillation and its relation to the monsoon rainfall. *Journal of Climatology*, *4,* 509-520.

Bohlinger, P., Sorteberg, A., & Sodemann, H. (2017). Synoptic conditions and moisture sources actuating extreme precipitation in Nepal. *Journal of Geophysical Research: Atmospheres*, *122*(23), 12653-12671. https://doi.org/10.1002/2017JD027543.

Cherchi, A., & Navarra, A. (2013). Influence of ENSO and of the Indian Ocean Dipole on the Indian summer monsoon variability. *Climate Dynamics, 41*(1), 81–103. https://doi.org/10.1007/s00382-012-1602-y.

Chowdhury, M.R. (2003). The El Niño-Southern Oscillation (ENSO) and seasonal flooding- Bangladesh. *Theoretical and Applied Climatology*, *76*(1–2), 105–124. https://doi.org/10.1007/s00704-003-0001-z

De Silva, T.M., & Hornberger, G.M. (2019). Identifying El Niño-Southern Oscillation influences on rainfall with classification models: Implications for water resource management of Sri Lanka. *Hydrology and Earth System Sciences, 23*(4), 1905–1929. https://doi.org/10.5.

194/hess-23-1905-2019

Fan, F., Dong, X., Fang, X., Xue, F., Zheng, F., & Zhu, J. (2017). Revisiting the relationship between the South Asian summer monsoon drought and El Niño warming pattern. *Atmospheric Science Letters,* 18(4), 175–182. https://doi.org/10.1002/asl.740

Fredriksen, H.B., Berner, J., Subramanian, A.C., & Capotondi, A. (2020). How does El Niño–Southern Oscillation change under global warming? A first look at CMIP6. *Geophysical Research Letters*, 47(22). https://doi.org/10.1029/2020GL090640

Gumus, V., & Algin, H.M. (2017). Meteorological and hydrological drought analysis of the Seyhan−Ceyhan River Basins, Turkey. *Meteorological Applications*, 24(1), 62–73. https://doi.org/10.1002/met.1605

Ichiyanagi, K., Yamanaka, M.D., Muraji, Y., & Vaidya, B.K. (2007). Precipitation in Nepal between 1987 to 1996. *International Journal of Climatology*, 27(13), 1753-1762. https://doi.org/10 :1002/joc.1492

Kansakar, S.R., Hannah, D.M., Gerrard, J., & Rees, G. (2004). Spatial pattern in the precipitation regime of Nepal. *International Journal of Climatology*, 24(3), 1645–1659. https://doi.org/10.1002/joc.1098

Karki, R., Hasson, S., Schickhoff, U., & Scholten, T. (2017). Rising precipitation extremes across Nepal. *Journal of Climate*, 5(1), 4. https://doi.org/10.3390/cli5010004

Karki, R., Talchabhadel, R., Aalto, J., & Baidya, S.K. (2015). New climatic classification of Nepal. *Theoretical and Applied Climatology,* 125(3–4), 799–808. https://doi.org/10.1007/s00704-015-1549-0

Mooley, D.A., & Parthasarathy, B. (1983). Variability of the Indian summer monsoon and tropical circulation features. *Monthly Weather Review*, 111(5), 967-978. https://doi.org/10.1175/1520-0493(1983)111

Muangsong, C., Cai, B., Pumijumnong, N., Hu, C., & Cheng, H. (2014). An annually laminated stalagmite record of the changes in Thailand monsoon rainfall over the past 387 years and its relationship to IOD and ENSO. *Quaternary International,* 349, 90–97. https://doi.org/10.1016/j.quaint.2014.08.037

Myronidis, D., & Nikolaos, T. (2021). Changes in climatic patterns and tourism and their concomitant effect on drinking water transfers into the region of South Aegean, Greece. *Stochastic Environmental Research and Risk Assessment*, 35(9), 1725–1739. https://doi.org/10.1007/s00477-021-02015-y

Niranjan Kumar, K., Rajeevan, M., Pai, D. S., Srivastava, A.K., & Preethi, B. (2013). On the observed variability of monsoon droughts over India. *Weather and Climate Extremes*, 1, 42–50. https://doi.org/10.1016/j.wace.2013.07.006

Patel, N.R., Chopra, P., & Dadhwal, V.K. (2007). Analyzing spatial patterns of meteorological drought using stndard precipitation index. *Meteorological Applications*, 14(4), 329-336. https://doi.org/10.1002/met.33

Pokharel, B., Wang, S.Y.S., Meyer, J., Marahatta, S., Nepal, B., Chikamoto, Y., & Gillies, R. (2020). The east–west division of changing precipitation in Nepal. *International Journal of Climatology*, *40*(7), 3348–3359. https://doi.org/10.1002/joc.6401

Ramanadham, R., Visweswara Rao, P., & Patnaik, J.K. (1973). Break in the Indian summer monsoon. *Pure and Applied Geophysics*, *104*(1), 635–647. https://doi.org/10.1007/BF00875908.

Rasmusson, E.M., & Carpenter, T.H. (1983). The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka, *Monthly Weather Review, 111*(3), 517-528.

Salerno, F., Guyennon, N., Thakuri, S., Viviano, G., Romano, E., Vuillermoz, E., Cristofanelli, P., Stocchi, P., Agrillo, G., Ma, Y., & Tartari, G. (2015). Weak precipitation, warm winters and springs impact glaciers of south slopes of Mt. Everest (central Himalaya) in the last 2 decades (1994-2013). *The Cryosphere*, *9*(3), 1229–1247. https://doi.org/10.5194/tc-9-1229-2015

Sein, Z.M.M., Ogwang, B., Ongoma, V., Ogou, F.K., & Batebana, K. (2015). Inter-annual variability of May-October rainfall over Myanmar in relation to IOD and ENSO. *Journal of Environmental and Agricultural Sciences, 4*, 28–36.

Sharma, S., Hamal, K., Khadka, N., & Joshi, B.B. (2020). Dominant pattern of year-to-year variability of summer precipitation in Nepal during 1987–2015. *Theoretical and Applied Climatology, 142*(3–4), 1071–1084. https://doi.org/10.1007/s00704-020-03359-1

Shrestha, A.B., Wake, C.P., Dibb, J.E., & Mayewski, P.A. (2000). Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale, *International Journal of Climatology*, *20*(3), 317–327.

Shrestha, D., Sharma, S., Hamal, K., Khan Jadoon, U., & Dawadi, B. (2020). Spatial Distribution of Extreme Precipitation Events and Its Trend in Nepal. *Applied Ecology and Environmental Sciences*, *9*(1), 58–66. https://doi.org/10.12691/aees-9-1-8

Shrestha, M.L. (2000). Interannual variation of Summer monsoon rinfall over Nepal and its relation to Southern Oscillation Index. *Meteorology and Atmospheric Physics*, *75*, 21-28.

Shrestha, S., Yao, T., Kattel, D.B., & Devkota, L.P. (2019). Precipitation characteristics of two complex mountain river basins on the southern slopes of the central Himalayas. *Theoretical and Applied Climatology*, *138*(1–2), 1159–1178. https://doi.org/10.1007/s00704-019-02897-7.

Sigdel, M., & Ikeda, M. (2010). Spatial and temporal analysis of drought in Nepal using standardized precipitation index and its relationship with climate indices. *Journal of Hydrology and Meteorology, 7*(1), 59–74. https://doi.org/10.3126/jhm.v7i1.5617.

Sigdel, M., & Ikeda, M. (2012). Summer monsoon rainfall over Nepal related with large-scale atmospheric circulations. *Earth Science & Climatic Change*, *3*(2), 112. https://doi.org/10.4172/2157-7617.1000112.

Sigdel, M., & Ma, Y. (2017). Variability and trends in daily precipitation extremes on the northern and southern slopes of the central Himalaya. *Theoretical and Applied Climatology*, *130*(1–2), 571–581. https://doi.org/10.1007/s00704-016-1916-5.

Sikka, D. (1980). Some aspects of the large-scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters. *Indian Academy of Sciences-Earth and Planetary Sciences, 89,* 179-195.

Trenberth, K.E. (1976). Spatial and temporal variations of the Southern Oscillation. *Quarterly Journal of the Royal Meteorological Society*, *102*(433), 639–653. https://doi.org/10.1002/qj.49710243310.

Varikoden, H., & Babu, C.A. (2015). Indian summer monsoon rainfall and its relation with SST in the equatorial Atlantic and Pacific Oceans. *International Journal of Climatology, 35*(6), 1192–1200. https://doi.org/10.1002/joc.4056.

Varikoden, H., Revadekar, J.V., Choudhary, Y., & Preethi, B. (2015). Droughts of Indian summer monsoon associated with El Niño and Non-El Niño years, *International Journal of Climatology*, *35*(8), 1916–1925. https://doi.org/10.1002/joc.4097.

Wang, B., Luo, X., & Liu, J. (2020). How robust is the asian precipitation-ENSO relationship during the industrial warming period (1901-2017)? *Journal of Climate, 33*(7), 2779–2792. https://doi.org/10.1175/JCLI-D-19-0630.1.

Wang, S.Y., Yoon, J.H., Gillies, R.R., & Cho, C. (2013). What caused the winter drought in western Nepal during recent years? *Journal of Climate*, *26*(21), 8241–8256. https://doi.org/10.1175/JCLI-D-12-00800.1

Webster, P.J., Magaña, V.O., Palmer, T.N., Shukla, J., Tomas, R.A., Yanai, M., & Yasunari, T. (1998). Monsoons: processes, predictability, and the prospects for prediction. *Journal of Geophysical Research: Oceans*, *103*(C7), 14451–14510. https://doi.org/10.1029/97jc02719.

Wright, P.B. (1975). *An index of the Southern Oscillation*. Climatic Research Unit School of Environmental Sciences University of East Anglia. Climatic Research Unit, Publications series, 4.

Yan, H., Sun, L., Wang, Y., Huang, W., Qiu, S., & Yang, C. (2011). A record of the Southern Oscillation Index for the past 2,000 years from precipitation proxies. *Nature Geoscience*, *4*(9), 611–614. https://doi.org/10.1038/ngeo1231.