Drought characteristics over Nepal Himalaya and their relationship with climatic indices

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Abstract
Understanding drought characteristics is vital for sustainable societal and ecosystem functioning, especially in ongoing climate change. The study investigates the drought characteristics over the Nepal Himalaya using the standardized precipitation index (SPI) based on monthly precipitation data from 220 ground stations between 1980 and 2016 at seasonal and annual timescales. The results show that occurrences of drought are more frequent after the 2000s, intensifying their severity and duration. The cumulative probabilities of short-term (SPI3) and long-term (SPI12) drought during the period 1980–2016 were 17.1% and 23.5%, respectively. The short-term drought over Nepal occurred with an average duration of 2.8 months and a severity of −4.3, whereas for long-term drought the duration and severity were 8.6 months and −13.9, respectively. Meanwhile, the seasonal drought shows that the spring and autumn drought events were slightly higher than summer and winter drought. The wavelet power spectrum shows the variability signals of winter, spring and summer drought were 2–8 and 8–16 years; however, the autumn drought index only varied at 2–8 years. The NINO3.4 is the primary controlling mode of variability for summer and annual drought, whereas the dipole moment index (DMI) is used for the autumn drought at an interannual timescale. The decadal variability of summer and annual drought is linked with the Pacific Decadal Oscillation, whereas winter and spring drought are linked to the Arctic Oscillation. Furthermore, the study contributes to the understanding of the drought characteristics and its controlling factors of variability over Nepal.

KEYWORDS
climatic indices, drought, Himalaya, standardized precipitation index (SPI), wavelet spectral analysis

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1 | INTRODUCTION

Frequent and severe droughts impact the meteorological, agricultural, hydrological and socioeconomic systems globally (Reichstein et al., 2013; Trenberth et al., 2014; Guo et al., 2019; Haile et al., 2020). Specifically, in the Tropics and Subtropics, drought has become more prevalent and is expected to intensify its duration and severity (Sheffield et al., 2012; Dai, 2013). From the beginning of the 21st century, South Asian regions have been frequently affected by severe drought, including Nepal, India and Pakistan (Miyan, 2015). The impacts of drought are significantly higher in rain-fed agricultural regions, causing crop failures and, consequently, food insecurity (Fahad et al., 2017; Mao et al., 2017; Hamal et al., 2020b). Therefore, region-specific explorations of droughts are necessary for efficient and effective drought monitoring and risk management.

In Nepal, two-thirds (68%) of the population depends on agriculture and it contributes one-third (34%) to the country’s economy (Bocchiola, 2017). Further, the country’s agriculture is excessively dependent on monsoon precipitation. Over recent years, Nepal has continuously suffered from dry and wet events due to the year-to-year variation of precipitation (Krishnamurthy et al., 2013; Hamal et al., 2020a). The above-normal precipitation in 1998, 2000, 2003, 2007 and 2008 resulted in floods across Nepal (Krishnamurthy et al., 2013). In contrast, low precipitation in 1992, 1994, 2005, 2006, 2008/2009 and 2015 triggered noticeable drought throughout the country (Adhikari, 2018). Notably, climate variability has induced and accelerated drought conditions in Nepal (Wang et al., 2013), impacting agricultural production (Hamal et al., 2020b). For instance, severe drought in 2008/2009 lowered the national production of major food crops (barley and wheat) by 15% (WFP, 2009). Similarly, the WECS (2011) reported that agricultural production decreased by 21,553 and 179,910 metric tons due to the 2005/06 and 2006/07 droughts, respectively. Moreover, the severe drought in 2015 caused food insecurity in western Nepal, affecting more than 80% of the population (Gyawali, 2016).

Many drought indices have been developed for drought calculation using different climatic parameters such as precipitation, temperature and evaporation. The widely used and most promising indices are the standardized precipitation index (SPI), the standardized precipitation evapotranspiration index (SPEI) and the Palmer drought severity index (PDSI) (Mishra and Singh, 2010; Zargar et al., 2011). The PDSI and SPEI use temperature and precipitation variables to calculate the water balance (Palmer, 1965; Vicente-Serrano et al., 2010), whereas the SPI uses only the precipitation variable (McKee et al., 1993). Precipitation is an important parameter of the global climate (Efstathiou and Varotsos, 2012), and the deficit of precipitation, that is, drought, affects the hydrological cycle (Van Loon, 2015). Further, Liu et al. (2015) revealed that below-normal precipitation is the primary reason for drought in some parts of China. For instance, precipitation has a major response to drought in southern China than temperature fluctuations (Chen and Sun, 2015). Furthermore, the weakening of the monsoon in the Indian region has increased the frequency and severity of drought (Davtalab et al., 2015; Mallya et al., 2016; Xu et al., 2018). Additionally, the SPI is the standard drought index recommended by the World Meteorological Organization (WMO), which characterizes drought by a simple methodology using precipitation data providing robust results (Sobral et al., 2019).

Few previous studies have analysed the spatial and temporal variation of drought across Nepal (Sigdel and Ikeda, 2010; Dahal et al., 2015; Khatiwada and Pandey, 2019). For instance, Sigdel and Ikeda (2010) analysed drought using precipitation data from 26 meteorological stations over Nepal between 1971 and 2003. Similarly, Dahal et al. (2015) used 40 stations in central Nepal during the period 1981–2013. Meanwhile, Khatiwada and Pandey (2019) tested different drought indices in western Nepal using data from 27 stations during the period 1981–2014, revealing the SPI’s capability to detect drought. All the above-mentioned studies considered data from limited stations and were mostly based on a regional scale with contrasting periods. Moreover, the seasonal drought mechanisms and their relationships with climatic indices are yet to be analysed from the past to the present. Therefore, the study analyses the national-scale drought characteristics from the SPI using data from 220 gauge stations over Nepal for about four decades (i.e. 1980–2016). Furthermore, the different seasonal drought variabilities are analysed by wavelet analysis and their relationship with climatic indices is assessed. The study will help researchers to understand drought and its related mechanism, which will eventually assist in planning and managing agriculture and water resources in Nepal.

2 | STUDY AREA

Nepal is a South Asian mountainous country, located between 26° 22' and 30° 27' N in latitude and between 80° 40' and 88° 12' E in longitude, covering a total area of 147,628 km². The country ranges from about 885 km in length (east–west) to about 193 km in width
(north–south), with an elevation range varying from about 60 m above mean sea level (masl) to 8,848.86 masl (Mount Everest) (Figure 1a). The country can be divided into five physiographical regions: Terai (< 700 masl), Chure (700–1,500 masl), Middle Mountain (1,500–2,500 masl), High Mountain (2,500–4,000 masl) and Himalaya (> 4,000 masl) (Koirala et al., 2019). The country features a very diverse climate, from tropical savanna at low elevations to polar frost in the high Himalayas, resulting from its uneven topography (Karki et al., 2016). Being located in the Tropic’s northern limit, the country receives summer monsoon and westerly winter precipitation (Kansakar et al., 2004; Duncan et al., 2013). The monsoon enters Nepal from the eastern region in early June and advances westwards, providing rainfall to the whole country within 10 days (DHM, 2017). The trans-Himalayan region has a dry climate since the main Himalayan range restricts monsoon moisture (Sharma et al., 2020a, 2020c). The southeast part of Nepal is greatly influenced by monsoon circulation, while the westerly derived circulation system dominates the northwest part of the country during winter (Nayava, 1980; Hamal et al., 2020a; Sharma et al., 2020d). Based on climatology, the four distinct seasons of Nepal are spring (March–May), summer monsoon (June–September), autumn (October–November) and winter (December–February). Moreover, the mean summer precipitation over the country during the period 1987–2015 is 1,685 mm (Sharma et al., 2020b).

3 | MATERIALS AND METHODS

3.1 | Data sources

The historical monthly precipitation records from 220 meteorological stations over Nepal (1980–2016) were collected from the Department of Hydrology and Meteorology (DHM), Government of Nepal (www.dhm.gov.np). The distribution of these stations is presented in Figure 1a. The precipitation records from the 220 selected stations were further checked for their historical temporal coverage, outliers and missing values. Therefore, to ensure the quality of the recorded data series, precipitation records were manually inspected for all stations during the study period. Any outlier values, for example, a dry month (October–May) precipitation value that is higher than those for monsoon months (June–September) were considered as missing values. Due to the application of large-scale data and precipitation being highly variable in space and time (Kidd and Huffman, 2011), the missing records were not filled in. Moreover, all the stations feature more than 80% of precipitation records (see Figure S1 in the additional supporting information). The data availabilities (%) of these selected stations for the study period are provided in Table S1 in the additional supporting information. The monthly cycle of precipitation is dominated by the South Asian Monsoon system, especially during June–September (Figure 1b). Additionally, the number of
stations at the 500 masl elevation range is presented in Figure 1c.

Besides, sea surface temperature (SST) with a spatial resolution of $0.25 \times 0.25^\circ$ was used from the recently released ERA5 datasets developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) (C3S, 2017). The climatic indices of monthly oceanic and atmospheric series: NINO3.4, Pacific Decadal Oscillation (PDO), Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) of the National Centers for Environmental Information (NOAA) were used in the present study. These datasets are freely available on the web portal of the NOAA’s Physical Sciences Laboratory (https://psl.noaa.gov/data/climateindices/list/). Moreover, the Indian Ocean Dipole Mode Index (DMI) dataset was downloaded from the Japan Agency for Marine–Earth Science and Technology (JAMSTEC) website (http://www.jamstec.go.jp/aplinfo/sintexf/).

### 3.2 SPI computation

The SPI was developed to monitor drought at different timescales (McKee et al., 1993). It is the most commonly used indicator globally to detect and characterize drought because of its limited data requirement and easy calculation procedure (Seiler et al., 2002; Cancelliere et al., 2007; Zhang et al., 2017). Nepal is an agricultural country where drought can impact different cropping stages of the seasonal crops (Hamal et al., 2020b); therefore, the SPI is computed at different timescales. The climatic variables were analyzed on seasonal and annual timescales using monthly climatic records. First, we calculated the SPI from one to 12 timescales and then selected SPI3, SPI3-February, SPI3-May, SPI4-September, SPI2-November, SPI12 and SPI12-December for the analysis of short-term, winter, spring, summer, autumn, long-term, and annual droughts, respectively. Physically, the SPI3 uses the precipitation of the current month and the past two months (e.g. SPEI3 in April [February–March–April]). Similarly, the SPI12 was calculated using precipitation of the concurrent month and the past 11 months, representing the long-term drought condition. The precipitation of December–February is used to calculate the winter drought index (SPI3-February). Moreover, the short-term and seasonal drought indices are applicable for agriculture assessment, whereas the long-term drought index is related to hydrological aspects (Almedeij, 2014; Pei et al., 2020). The value of the dryness and wetness condition lies at $\leq -1$ and $\geq 1$, respectively. The different categories of drought are provided in Table 1.

### 3.3 Wavelet analysis

The wavelet transform is a method of decomposing a time series to explore the signals in the time and frequency domain (Torrence and Compo, 1998). The continuous Morlet wavelet transform is used to understand the spatial and temporal dominant spectral mode in the seasonal and annual drought indices. Lee and Yamamoto (1994) provided a detailed method for the calculation of the wavelet analysis, and several previous studies have used wavelet analysis to visualize the potential signals embedded in the time series (Torrence and Compo, 1998; McHugh, 2006; Dieppois et al., 2016; Tadeyo et al., 2020; Sharma et al., 2020b).

### Table 1 Drought classification based on standardized precipitation index (SPI) values

| SPI          | Drought category |
|--------------|------------------|
| $-1.5 < SPI \leq -1.0$ | Moderate         |
| $-2.0 < SPI \leq -1.5$ | Severe           |
| $\leq -2.0$    | Extreme          |

After calculating the SPI, drought events were classified into three categories (Table 1) using the threshold level (SPI $\leq -1$). The duration of the drought events (De) is months between the drought start time ($ti$) and drought end time ($te$) (Mishra and Singh, 2010). The sum of SPI $\leq -1$ for each drought event is known as severity ($Se$) (Equation 1). Drought intensity ($Ie$) was calculated as the ratio of $Se$ to $De$ (Equation 2):

$$Se = \left( \sum_{i=1}^{n} SPI_i \right) \epsilon.$$  \hspace{1cm} (1)

$$Ie = \frac{Se}{De}.$$  \hspace{1cm} (2)

The total drought occurrences during the study period were calculated using drought frequency. Further, drought frequency was calculated using cumulative curves (gamma distribution function), which show the probability of the observations below SPI $\leq -1$ (Equation 3):

$$F(t) = \frac{1}{N} \sum_{i=1}^{N} 1(X_i < t).$$  \hspace{1cm} (3)

where $N$ is the months of observations; $X_i$ is the number of values $< t$; and $t$ is the threshold value of drought.
Correlation analysis

Pearson correlation analysis (Ross, 2017) was performed between SPIs at different timescales with the SST anomalies and climatic indices (NINO3.4, dipole moment index (DMI), North Arctic Oscillation (NAO), Arctic Oscillation (AO) and Pacific Decadal Oscillation (PDO)). The significance of the relationship was tested at a 90% confidence level.

RESULTS

Drought variation at a different timescale

The temporal evolution of the SPI at 1–12 timescales represents the development pattern of dryness and wetness during the period 1980–2016 over Nepal (Figure 2). During the study period, the major drought events were observed in 1982, 1985, 1991–1992, 1994, 2005–2006, 2008–2009, 2012, 2013 and 2015. Notably, 1992 and 2015 were extreme drought (SPI ≤ −2) years, which occurred from the SPI1 to SPI12 timescales (Figure 2). Moreover, aggregated and prolonged drought events were more frequent after 2005.

The temporal variation of short-term drought (SPI3) shows that fluctuating frequency is relatively higher, alternating dry–wet conditions throughout the study period (Figure 3a). The country had experienced extreme short-term drought (SPI3 ≤ −2) events in 1992, 1998, 2005–2006, 2009 and 2015. The seasonal droughts were more frequent after the 1990s with intensifying severity and duration; meanwhile, consecutive drought events were observed between 2005 and 2016 (Figure 3a). The SPI12 represents the long-term water deficiency for almost about a year with considerable fluctuation of the dry and wet events than the SPI3 (Figure 3b). A total of eight long-term drought events (1982–1983, 1991–1993, 1994–1995, 2005–2006, 2008–2009, 2012–2013, 2014 and 2015–2016) were observed during the study period (Figure 3b). Most of these yearly drought events mainly occurred after 2005, suggesting that drought has increased in recent decades over the study region.

Drought characteristics

The cumulative drought frequencies (moderate, severe and extreme) at the SPI3 and SPI12 were 17.1% and
23.5%, respectively, during the study period (Figure 4a). The moderate drought at short- and long-term timescales had the highest frequencies of 10.4% and 13.9%, respectively, over the study region (Figure 4b, c). It also revealed that moderate short-term (long-term) drought frequencies were 2.9 (3.1) and 3.8 (4.5) times higher than the severe and extreme drought frequencies, respectively (Figure 4b). Meanwhile, severe and extreme drought frequencies at the SPI3 were 3.6% and 2.7% (Figure 4b), whereas the severe drought frequency was 1.5 times higher than the extreme drought frequency in the long-term timescale (Figure 4c). Overall, the results indicate that the moderate drought was higher than the severe and extreme droughts during the study period over Nepal (Figure 4).

The average drought duration, severity and intensity during the study period are presented in Figure 5. At a short-term timescale, the average drought duration was 2.8 months, with severity and intensity of $-4.3$ and $-1.53$, respectively (Figure 5a). The longest short-term drought was observed in 2015/2016 with a duration of 9 months and a total severity of $-13.80$ (Table 2). Moreover, the average duration of 8.6 months with a severity (intensity) of $-13.9$ ($-1.6$) was observed at the long-term timescale (Figure 5b). The duration, severity and intensity at the SPI12 were higher than at the SPI3. Further, the increase in duration leads to an enhanced drought severity and intensity at a longer timescale. Moreover, 1991–1993 was the drought period with maximum duration, severity and intensity of 20 months, $-49.40$ and $-3.80$, respectively (Table 2).

### 4.3 | Seasonal drought variation

Figure 5 presents the seasonal and annual drought variations over Nepal from 1980 to 2016. Generally, the SPI12-December indicates the annual drought with an all-year-round water deficit condition. Additionally, the short-term water-scarce conditions at the SPI3-February, SPI3-May, SPI4-September and SPI2-November represent the winter, spring, summer and autumn droughts, respectively. During the study period, six winter drought events are observed in 1999, 2001, 2006, 2008, 2009 and 2016, mainly after the late 1990s over the study region (Figure 6a). Further, extreme winter drought events were observed in 2006 and 2009. It is worth noting that most of the drought events are observed in recent years, revealing the decadal variability of drought. Spring droughts have been widespread since the mid-1980s, with a total of seven drought events in 1985, 1986, 1992, 1999, 2001, 2006 and 2009 (Figure 6b). The only two summer drought events were observed before 2000 (i.e. 1982 and 1992), whereas

| SPI    | Maximum (minimum) duration (months) | Maximum (minimum) severity | Maximum (minimum) intensity |
|--------|-------------------------------------|---------------------------|---------------------------|
| SPI3   | 9 (1)                               | $-13.80$ ($-1.0$)         | $-1.53$ ($-1.0$)          |
| SPI12  | 20 (1)                              | $-49.40$ ($-1.1$)         | $-3.80$ ($1.1$)           |

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**Figure 4** (a) Cumulative frequency of SPI3 and SPI12; and (b, c) frequencies of moderate, severe and extreme drought at (b) SPI3 and (c) SPI12 over Nepal, 1980–2016

**Figure 5** Average duration, severity and intensity of (a) SPI3 and (b) SPI12 over Nepal, 1980–2016

**Table 2** Maximum and minimum duration, severity, and intensity of SPI3 and SPI12 over Nepal during the study period
More frequent drought events were observed after the 2000s (i.e. 2005, 2006, 2009 and 2015) (Figure 6c). Autumn droughts events were relatively higher in the 1980s and early 1990s (1981, 1984, 1988, 1991 and 1994) (Figure 6d). However, only two autumn drought events were observed after the 2000s (2000 and 2012) in Nepal. A total of nine annual drought events (1982, 1992, 1992, 1994, 2005, 2006, 2009, 2012 and 2015) were observed during the study period (Figure 6e). Since the summer precipitation accounts for approximately 80% of the annual precipitation, the year-to-year variation of annual and summer droughts is almost similar (Figure 6c, e).

4.4 | Wavelet spectrum analysis of the seasonal drought

Figure 7 illustrates the Morlet wavelet power spectrum analysis of seasonal and annual drought. The time-series of winter, spring, summer, autumn and the annual drought indices were passed through the Morlet wavelet power spectrum to investigate the embedded signals for drought variation. For the winter drought index, a significant signal is observed between 1995 and 2010, giving a 2–4 year message of variability (Figure 7a). Moreover, the message of decadal variability between eight and 16 years
was observed in the same period. The inseparable signals were observed for the spring drought index showing the interannual (between two and eight years) and decadal (between eight and 16 years) variability (Figure 7b). The decadal signal of the summer drought variability was observed in 2000 (Figure 7c). The summer drought index further indicates three significant signals between two and eight years of the power spectrum during the study period. The autumn drought index only varies at the interannual timescale (between two and eight years) in Nepal (Figure 7d). Similar to Figure 6c, e, the summer and annual drought indices have similar a variability of signals during the study period (Figure 7c, e).
The SST anomalies have a significant role in the inter-annual and decadal variability of the precipitation and its extremities (Sharma et al., 2020b). Thus, the correlation is calculated to analyse the relationship between the detrended drought indices and the corresponding season of detrended SST anomalies during the study period (Figure 8). For the winter drought index, small patches of the significant relationship were observed over the Pacific and Indian oceans (Figure 8a); however, the signals were more pronounced for the spring drought index (Figure 8b). For the summer drought index, the Pacific and Indian oceans’ relation becomes more vivid (Figure 8c). The significant correlation over the equatorial eastern and western Pacific shows the characteristics of the El Niño Southern Oscillation (ENSO). The summer drought corresponds well with the negative phase of the NINO3.4, giving its significant correlation co-efficient of −0.63, p < 0.1 (Table 3). In contrast, the autumn drought index shows the characteristics of the DMI, with positive SST anomalies over the eastern tropical Indian Ocean and negative SST anomalies in the western tropical Indian Ocean (Figure 8d). The result shows that the autumn drought depends entirely on the negative phase of the DMI (R = −0.29, p < 0.1), whereas ENSO’s influence was not observed. Since annual precipitation is dominated by summer precipitation (approximately 80%), a similar SST anomalies variation and relationship with their indices were found over the Indian and Pacific.
oceans (Figure 8e). Moreover, the significant influence of the ENSO is observed in the summer and annual drought variability; meanwhile, the influence of the DMI is not observed (Table 3).

Further, a positive relation is detected in the Pacific Ocean (north of 20°–60° N) for winter, spring, summer and annual droughts, suggesting the influences of the PDO (Figure 8a–c, e); however, the PDO can only modulate the interdecadal variation of summer and annual drought, as indicated by the significant relationship in Table 3. Furthermore, a significant correlation is observed between winter and spring droughts with the AO (Table 3), indicating the decadal variability of drought. Meanwhile, summer, autumn and annual drought are not linked to atmospheric indices such as the NAO and AO.

5 | DISCUSSION

The spatio-temporal variation of drought characteristics was analysed over the southern slope of the central Himalaya in Nepal during the period 1980–2016. The study applied large-scale observed data (i.e. 220 stations) for better drought representation, which overcomes the previous study of Sigdel and Ikeda (2010) conducted a decade ago with limited data. The results showed that the frequent occurrence of the drought after the 2000s occurred with an intensification of its severity and duration at short- and long-term timescales in the country. The major drought events were observed during the periods 1982–1983, 1992–1993, 1994–1995, 2005–2006, 2008–2009, 2011–2012, 2013 and 2015, indicating increased drought events in recent decades. Similarly, the previous studies conducted in western and central Nepal have also shown the occurrences of the major drought events in recent years (Dahal et al., 2015; Khatiwada and Pandey, 2019).

Several studies reported increased drought events, intensity, severity and frequency over South Asia in recent decades (Kumar et al., 2013; Miyan, 2015; Mallya et al., 2016). For instance, Ma et al. (2019) found that a decrease in monsoon precipitation led to an increase in drought over South Asia, particularly after the 2000s. Further, Roxy et al. (2015) found reduced precipitation over the Indian subcontinent due to weakened mean southwesterly winds. In addition, the drying signals at the decadal timescale are due to weakened wind anomalies (Hernandez et al., 2015). Moreover, such decadal variation of the monsoon manifests droughts and floods episodes over the Indian subcontinent (Krishnamurthy and Shukla, 2000; Kumar et al., 2013; Miyan, 2015; Mallya et al., 2016).

Nepal has experienced severe, moderate and extreme drought at short- and long-term timescales with cumulative frequencies of 17.1% and 23.5%, respectively. The weakening of the South Asian Summer Monsoon (SASM) has increased drought frequency, duration and severity in the recent past (Kumar et al., 2013; Hernandez et al., 2015; Ma et al., 2019). For instance, a deficit of all-India-averaged monsoonal rainfall, the drought of 2015/2016 was registered as one of India’s worst and extreme droughts in the last 110 years (Mishra et al., 2016; Abhilash et al., 2019). A recent study by Aadhar and Mishra (2017) also mentioned that more than 25% of South Asian regions (including Nepal) were under severe drought during the period 1982–2007. The highest severity between July 2015 and March 2016 (see Figure S2 in the additional supporting information) might be related to changes in monsoonal precipitation over the study region.
Strong El Niño years (2014–2016) and the warming of the Indian Ocean had resulted in a substantial precipitation deficit over the Indo-Gangetic Plain (Mishra et al., 2016). Moreover, the causes and physical mechanism of increased drought severity and intensity are related to the SST anomalies and changes in atmospheric circulation (Kumar et al., 2013; Wang et al., 2013).

The declining trend of the seasonal precipitation at an interannual timescale might be the reason for the increased drought over Nepal in recent years (Panthi et al., 2015; Khatiwada et al., 2016). The wavelet power spectrum analysis showed 2–8 and 8–16 years of variability signals for winter, spring, summer and annual droughts from 1980 to 2016. Meanwhile, interannual and decadal variability of winter and summer precipitation signals are observed over the country (Hamal et al., 2020a; Sharma et al., 2020b). Moreover, the dry events during summer at an interannual timescale over Nepal are caused by the summer El Niño (Sharma et al., 2020b). A significant correlation was found between the SPI and SST anomalies over the Pacific Ocean, suggesting that the ENSO is the prominent forcing for the interannual variability of annual and summer drought in Nepal. The warm SST anomalies over the Pacific disturbed the monsoon circulation by delaying monsoon precipitation and causing a precipitation deficit in South Asia (Mishra et al., 2016; Joshi and Kar, 2018; Sharma et al., 2020b).

Several studies found a significant influence of Indian Ocean Dipole (IOD) on the SASM (Ashok et al., 2001; Krishnaswamy et al., 2015; Ha et al., 2018); however, the relationship between the DMI and drought was not observed in the present study. Ha et al. (2018) analysed the SASM index in the region of 60–100° E and 5–22.5° N (which includes most of the Indian region), but Nepal (80–89° E and 26–31° N) was excluded. Therefore, we calculated the correlation between the SASM and summer drought index and found a non-significant positive correlation (Figure 9). However, a significant negative correlation was observed with the Indian Ocean, giving the Indian Ocean Basin Mode (IOBM) (Figure 8c). A recent study by Sharma et al. (2020b) showed that the IOBM has a significant influence on summer precipitation and causes a dipole pattern of precipitation. Moreover, the present study also shows the significant relationship between summer and annual drought with the PDO. Similarly, Krishnamurthy and Krishnamurthy (2014) and Watanabe and Yamazaki (2014) found a strong relationship between the SASM and PDO, where the warm phase of the PDO is related to drought events.

The autumn drought events were relatively higher in the 1980s and early 1990s (1981, 1984, 1988, 1991 and 1994), whereas only two events were observed after the 2000s (2000 and 2012) in Nepal. The autumn drought index showed variability between two and eight years related to the negative phase of the DMI. A similar result was observed by Gao et al. (2019) during negative IOD years, which witnessed a reduction of spring rainfall with an increase in drought. The IOD appears to be stronger in September–November with a higher SST in the Eastern region and a lower SST in the western region of the Indian Ocean (Chongyin and Mingquan, 2001) (Figure 8d). Further, the strong DMI between the 1980s and the 1990s (Maruyama et al., 2011; Lim et al., 2017) might be the reason for frequent occurrences of autumn drought over Nepal. The westerly disturbances primarily contribute to winter precipitation in Nepal, which has a different phenomenon than summer precipitation (Dimri, 2013; Hamal et al., 2020a). During the study period, drought events had occurred mainly after the 2000s (2001, 2006, 2008, 2009 and 2016) (Figure 5a), showing the decadal variability of winter drought relating to the AO. Similarly, Wang et al. (2013) found that the decadal variability of the winter drought is linked to the AO, initiating a tropospheric short wave train across Eurasia and South Asia.

6 | CONCLUSIONS

The present study investigated the drought characteristics over Nepal using the standardized precipitation index (SPI) index based on precipitation data from 220 rain gauge stations between 1980 and 2016 at different timescales (SPI3, SPI3-February, SPI3-May, SPI4-September, SPI2-November, SPI12 and SPI12-December). Furthermore, the correlation between seasonal drought and climatic indices—NINO3.4, dipole moment index (DMI), North Arctic Oscillation (NAO), Arctic Oscillation (AO) and Pacific Decadal Oscillation (PDO)—were also analysed. The major drought events were observed in 1982, 1985, 1991–1992, 1994, 2005–2006, 2008–2009, 2012, 2013 and 2015. Further, frequent drought occurrences were observed after the 2000s with intensifying severity and duration. The cumulative drought frequencies analysed at short-term (SPI3) and long-term (SPI12) timescales for 37 years were 17.1% and 23.5%, respectively. Moreover, the severe and extreme drought frequencies in the short-term timescale were 3.6% and 2.7%, with a difference < 1%. At a long-term timescale, the severe drought frequency was 1.5 times higher than the extreme drought frequency. During the study period, short-term drought has the duration, severity and intensity of 2.8 months, −4.3 and −1.5, respectively, whereas they are 8.6 months, −13.9 and −1.6 for long-term drought, indicating the long-term drought is relatively more prolonged and severe.
Further, the seasonal drought analysis showed that the spring and autumn drought events (seven) were slightly higher than summer and winter drought events (six) during the study period. The spring and autumn drought occurrences have been widespread since the mid-1980s, whereas the summer and winter droughts mainly occurred after the 2000s. For instance, summer drought events almost doubled after the 2000s, that is, from two events (1982 and 1992) to four events (2005, 2006, 2009 and 2015). Meanwhile, the wavelet power spectrum analysis of winter, spring, and summer drought showed the 2–8 and 8–16 years of variability signals. In contrast, the autumn drought index only varies at 2–8 years over the country. The summer and annual drought variabilities are related to the NINO3.4, whereas the DMI for the autumn drought is related at an interannual timescale. Moreover, the decadal variabilities of summer and annual droughts are linked with the PDO, while the winter and spring droughts are linked with the AO. Furthermore, the current study revealed the impacts of different climatic indices on droughts; however, future studies should focus on the mechanism for interannual and decadal drought variability and associated circulations over Nepal.

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CONFLICT OF INTEREST
The authors declare they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in the paper.

AUTHOR CONTRIBUTIONS
Shankar Sharma: conceptualization, investigation, methodology, visualization, formal analysis and writing—original draft; Kalpana Hamal: conceptualization, investigation, validation, review and writing—review and editing; Nitesh Khadka: validation, data curation, review and writing—review and editing; Dibas Shrestha: supervision and writing—review; Deepak Aryal: supervision and writing—review; Sudeep Thakuri: supervision, conceptualization, review and writing—review and editing.

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**Note:** The text above is a subset of the full text and may not represent the entire document.
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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of this article.

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