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The spatio-temporal characteristics of drought across Tibet, China: derived from meteorological and agricultural drought indexes

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Abstract

The droughts normally lead to devastating and long-lasting damage to agriculture, economy, and ecosystem, especially in Tibet Autonomous Region (hereafter Tibet) where ecosystem is fragile as a result of its special topographic, geomorphic, and climatic conditions. Due to limited observational data in this region, how often and where these droughts occur is not well understood. In this study, droughts intensity and frequency, as well as dryness condition over Tibet were assessed by using the Standardized Precipitation Evapotranspiration Index (SPEI) with meteorological data from 38 stations during period of 1971–2014. Temperature Vegetation Dryness Index (TVDI) was used to compared with SPEI based on observed drought area of Tibet. Moreover, the dryness condition was explained by the contribution of meteorological factors according to the method of contribution rate. Results indicated that dryness conditions were aggravating during the period 1971–2014 across Tibet. Besides, drought intensity and frequency presented considerable decadal variation over the past 44 years with more frequent moderate and severe drought occurring in period of 1981–1990 and 2001–2014 compared with other periods. This highlighted that Tibet has gone through serious drying in the 1970s and since 2000. Factor analysis indicated that precipitation played the most important role in the variation of SPEI-12M. Both drought indexes could effectively detect drought events over Tibet from 2001 to 2014. Investigating and evaluating drought characteristic, causes and drought indexes effectiveness provide essential information for balanced water resource allocation and utilization and drought prevention.

1 Introduction

Drought is one of the most widespread and long-lasting natural hazards that affects water quantity and quality, agricultural production, and natural ecosystems (McKee et al. 1993; Vicente-Serrano et al. 2010; Piao et al. 2010; Mishra and Singh 2010). Insufficient precipitation plays a prominent role in drought events occurrence (Herrera-Estrada et al. 2017; Roundy et al. 2013). Other factors such as evaporation, soil moisture, regional water supply, and even human agriculture and economic activities also act vital roles in creating drying conditions (Chen and Sun 2015; Das et al. 2016; Mei et al.

2018; Mishra and Singh 2011). Most of the world is becoming vulnerable to drought (Hernandez and Uddameri 2014; Chen and Sun 2015; Dhorde and Patel 2016), and drying trends have been examined over India, Europe, Central China, and Australia (Thomas and Prasannakumar 2016; Mishra and Singh 2011; Wang et al. 2017; Bond et al. 2008). Increased wildfires, decreased hydro-power generation, and decreased domestic water supply throughout populated areas due to drought could lead to substantial loss to societies and ecosystems. The economic costs of drought were estimated by the US Federal Emergency Management Agency (FEMA) as $6 to $8 billion per year; these estimates are higher than those associated with other meteorological disasters (Wilhite 2000). Thus, drought frequency, severity, causes, and spatio-temporal extent are critical components that should be clearly quantified, and it will provide and convey information to decision makers for reducing or avoiding the impact of droughts and developing effective drought detecting system (Hayes et al. 2011).

Drought indexes are effective in detecting and forecasting drought events and widely used to quantify their intensity, frequency, duration, and temporal-spatial variation.

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Numerous indexes and models have been developed to date based on observed meteorological variables including precipitation, temperature, and evaporation as well as other observations such as the Normalized Difference Vegetation Index (NDVI) and soil properties (Herrera-Estrada et al. 2017; McKee et al. 1993; Kogan 1995; Palmer 1968; Wells 2003; Byun and Wilhite 1996), such as Palmer Drought severity Index (PDSI) (Plamer 1965), the rainfall anomaly index (RAI) (Van Rooy 1965), drought area index (DAI) (Bhalme and Mooley 1980), China-Z index (CZI) (Wu et al. 2001), Temperature Vegetation Dryness Index (TVDI) (Sandholt et al. 2002), standardized precipitation index (SPI) (Patel et al. 2007), Vegetation condition index (VCI) (Kogan 1995), and SEPI (Vicente-Serrano et al. 2010). As a meteorological drought index depending on precipitation and potential evapotranspiration, SPEI was considered as universal index to detect and monitor drought condition under the context of global warming due to its multiscale characteristics (Vicente-Serrano et al. 2010, 2012). SPEI has been widely used in time series of short- and long-term droughts reconstructing and monitoring in many regions of the world (Hernandez and Uddameri 2014; Chen and Sun 2015; Bao et al. 2015; Das et al. 2016). As an agricultural drought index, TVDI depends on the relationship between Normalized Difference Vegetation Index (NDVI) and land surface temperature (Ts) and droughts over regional scale even national scale be identified by using it in a number of previous studies (Dhorde and Patel 2016; Liang et al. 2014; Wang et al. 2004). The concept and usage of agricultural drought index and meteorological drought indexes are different where SPEI reflects water deficit in the air, whereas TVDI mainly focuses on soil moisture. Agricultural drought emphasizes the influence of droughts on human beings, and meteorological droughts are regarded as pure climate anomalies. Nevertheless, these two indexes have close connections and are closely correlated under most conditions. For instance, infiltration (being considered in agricultural drought index) starts with a precipitation event (being considered in meteorological drought index). As such, meteorological and agricultural drought may happen concurrently. Furthermore, ET is an important element in these two indexes since it controls both crop physiological and meteorological processes. Therefore, comprehensive application of multiple drought indexes to evaluate and capture different aspects of drought conditions is the current trend which has already been approved by numbers of studies (Hao and Singh 2015; Gao et al. 2011; Morid et al. 2006).

Situated in the high-altitude Tibetan Plateau who acts the significant role of "source of rivers," Tibet is a region where major rivers of China originate from and is famous for Water Tower of Asia (Zhao et al. 2006). These rivers not only provide water and hydropower to the middle and low reaches but also affect downstream regions through flooding and drought. The ecosystem of Tibet is fragile as a result of its special geological, topographic, and weather conditions (Zhao et al. 2006). Thus, Tibet is frequently influenced by natural disasters such as drought, windstorms, and frost. Frequent droughts would further intensify water stress and bring enormous loss to this region's agriculture. To reduce or eliminate the impact of drought and increase the accuracy of forecasting drought events throughout Tibet, knowledge and information concerning the characteristics of drought events over the past decades and their correlation with associated meteorological factors are highly required. Analysis of past decades droughts could offer us valuable information for developing integrated drought warning system to prevent or reduce droughts' impacts (Deng et al. 2017; Li et al. 2015). However, to our knowledge, the spatial and temporal pattern of drought occurrences and the causes of drought throughout this region has not been thoroughly investigated. A single drought index may not be robust enough to cover drought events over a certain region where it is defined as complexity and diversity in meteorological and topographical conditions (Zhang et al. 2017). For this reason, the accurate and timely detection of drought may require using more than one drought indexes across Tibet. In particular, due to the limited number of meteorological stations and their uneven distribution, using only these observed meteorological data to characterize drought events may bring uncertainties stemming from large spatial variabilities. Therefore, in this study, we focus on the more frequently occurring meteorological drought and agricultural drought, as various characteristic of meteorological drought was closely linked to agricultural impacts by agricultural drought (Wilhite 2000). Moreover, in consideration of SPEI's and TVDI's robustness, dimensionality, and popularity, we use the remote-sensing-based drought index—TVDI and meteorological-observed-based drought index—SPEI to analyze the variations in drought occurrences in Tibet.

The objectives of this study are to (1) investigate the intensity and frequency of drought events and their spatial-temporal patterns; (2) identify the contributions of major meteorological factors to dryness condition; and (3) compare and evaluate the performance of TVDI and SPEI based on the observed annual agricultural drought area. Survey on drought condition, causes, and comparison of TVDI and SPEI indexes over Tibet will provide a better understanding of drought events and lay a foundation to further drought forecasts and predictions across Tibet.

2 Data and methods

2.1 Study area

Located in Tibetan Plateau in Asia, between coordinates 78°24′–99°06′ E and 26°44′–36°32′ N, Tibet covers an area of about 1.22×10^6 km^2 with mean altitude higher than

4000 m and it is widely known as the roof of the world (Wu et al. 2017). As a unique geographical unit, Tibet is quite distinctive from neighboring regions. Dominated by high mountains, the complex terrain generally slopes downward from northwest to southeast. The region is characterized by various types of geomorphology including plains, platforms, hills, mountains, deserts, and glaciers, which influence atmospheric circulation across the region. As a result, Tibet encompasses heterogeneous meteorological zones. Southern Tibet is influenced by warm and humid airflow from the Indian Ocean; thus, the area has a humid and warm climate with annual mean temperature of 8 °C and annual average precipitation of 600 mm. In contrast, northern Tibet is characterized by a dry continental climate with annual mean temperatures < 0 °C and annual average precipitation < 300 mm (Xu et al. 2008). Tibet has the highest annual solar radiation in China, with annual sunshine duration of 3100 to 3400 h. The frost-free season over most of the area is longer than 120 to 140 days, which benefits agricultural production. The total annual radiation increases gradually from east to west; the Ali region has the highest radiation, whereas the southeast has the lowest radiation. Overall, compared with other regions of China with same latitude, Tibet is colder and drier (Fig. 1).

2.2 Data processing

Observational meteorological data of 38 stations were obtained from the National Meteorological Information Centre of China across Tibet during 1971 to 2014 including daily maximum, minimum, and average air temperatures; wind speed; sunshine duration; relative humidity; atmospheric pressure; and precipitation. Missing data were filled with extrapolations from neighboring stations (Song et al. 2010). The Department of Plantation, Ministry of Agriculture, archives data on drought areas across Tibet (http://202.127.42.157/moazzys/zaiqing.aspx), and such data were used for evaluating and validating the performance of the TVDI and SPEI drought indexes.

MOD11A2 (8-day average land surface temperature (LST)) and MOD13A2 (Vegetation Indexes) were provided by the Land Processes Distributed Active Archive Center (LP DAAC). MOD13A2 includes the NDVI and Enhanced Vegetation Index (EVI). In this study, two sequential 8-day MOD11A2 were averaged to 16 days to keep pace with MOD13A2. Data pre-processing included radiation correction and geometric correction. Then, the MOD11A2 and MOD13A2 data were mosaicked and resampled. The resample method is Nearest Neighbor, and projection is set as Universal Transverse Mercator (UTM) Projection. As to the trend analysis of SPEI and meteorological factors of each station, linear tendency estimation and significance t test were used (Dombrovskiy et al. 2007). The linear regression is an approach to modeling the relationship between a scalar response (or dependent variable) and
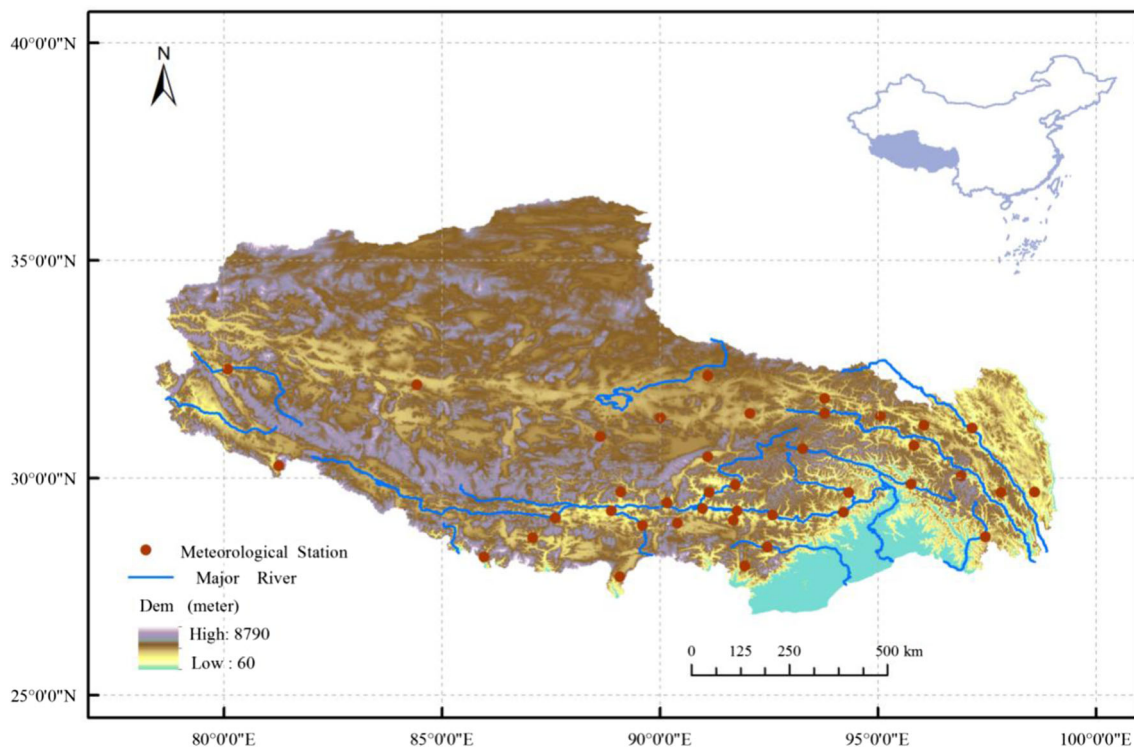

Fig. 1 Study domain and the distribution of meteorological observation stations across Tibet Autonomous Region (Tibet)

one or more explanatory variables (or independent variables) (Freedman 2009).

2.3 Methodology

Based on the SPI method (Patel et al. 2007), Vicente-Serrano et al. (2012) developed the SPEI by retaining the multi-scalar advantages, which can inspect and evaluate the drought condition under the climate warming. The calculation of SPEI is straightforward, and the time scale is flexible; therefore, this index has been widely used and validated for drought monitoring. SPEI depends on two major variables: potential ET (PET) and precipitation (P). PET was estimated with FAO-56 Penman-Monteith (Eq. 1; Allen et al. 1998):

$$PET_i = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \quad (1)$$

$$D_i = P_i - PET_i \quad (2)$$

where PET_i is the potential ET of station i, R_n is the net radiation, G is the soil heat flux density, T is the mean daily air temperature, u_2 is the wind speed at a 2-m height, e_s is the saturation vapor pressure curve, e_a is the actual vapor pressure, Δ is the slope vapor pressure curve, γ is the psychrometric constant, and D_i is the difference between precipitation and potential ET. Accumulated difference between precipitation and potential ET was calculated at different time scales (e.g., 3 months, 6 months, 12 months). Then, a three-parameter log-logistic distribution was selected to model the accumulated difference series. Finally, SPEI was obtained using the probability distribution function based on the standardized log-logistic distribution (Vicente-Serrano et al. 2010). When the value of SPEI is lower than − 0.5, there are droughts occurred and lower value of SPEI (i.e., more negative) means that the drought is more severe. In contrast, positive value of SPEI indicates that there are on droughts. The impacts of drought events on agriculture depend on their frequency and intensity. SPEI-12M and SPEI-3M were calculated from accumulation of water balance in the 12 and 3 months, respectively (Patel et al. 2007). In this study, 12-month SPEI of December (SPEI-12M) and 3-month SPEI of May, August, November, and February (SPEI-3M) were generated for representing annual and seasonal drought events,

respectively. By using SPEI-12M, we could track the trend of drought characteristic in the long run and identify the climatic condition of Tibet in general. For SPEI-3M, it is able to reflect short-term agricultural droughts and it is more reasonable to use it when we analyze drought variation of intensity and frequency in every short-run 10 years. For comparison in this study, SPEI was also generated on 16-day (SPEI-16D) intervals to keep pace with TVDI (TVDI-16D).

TVDI was developed by Sandholt et al. (2002) based on vegetation index and land surface temperature. The advantages of this method include definite physical processes, a very fewer input variables, and low spectral resolution requirements of the remotely sensed data so that it can be easily applied over a large area (Liang et al. 2014). The TVDI was calculated using the following steps:

$$TVDI = \frac{T_s - T_{smin}}{T_{smax} - T_{smin}} \quad (3)$$

$$T_{smin} = a_{min} - b_{min} \cdot NDVI \quad (4)$$

$$T_{smax} = a_{max} - b_{max} \cdot NDVI \quad (5)$$

where NDVI is the normalized difference vegetation index; T_s is the surface temperature; T_{smax} and T_{smin} are the maximum and minimum surface temperature, which correspond to the dry and wet edges of the *NDVI*, respectively; and a_{max}, b_{max} and a_{min}, and b_{min} are the intercept and slope of the dry and wet edge equations, respectively. By the method of linear regression, value of a_{max}, b_{max} and a_{min}, and b_{min} could be obtained. The TVDI ranges between 0 and 1; higher value indicates a more severe drought, and lower value indicates a weaker drought. The monthly and annual TVDI is the average value from the 16-day TVDI (TVDI-16D) at monthly and annual time steps, respectively (Liang et al. 2014). The drought classifications based on the TVDI and SPEI are listed in Table 1 (Chunqiao et al. 2011; Yan-fei et al. 2016).

We use drought intensity and frequency to characterize the inter-decadal variation of drought. The drought intensity is calculated as (Yan et al. 2017):

$$S = \left| \frac{1}{m} \sum_{i=1}^{m} SPEI_i \right| \quad (6)$$

Table 1 Drought classifications based on SPEI and TVDI

Drought class of SPEI	SPEI	Drought class of TVDI	TVDI
Non-drought	$-0.5 < SPEI \leq 0.5$	Wet	$0 < TVDI \leq 0.2$
Mild drought	$-1.0 < SPEI \leq -0.5$	Normal	$0.2 < TVDI \leq 0.4$
Moderate drought	$-1.5 < SPEI \leq -1.0$	Mild drought	$0.4 < TVDI \leq 0.6$
Severe drought	$-2.0 < SPEI \leq -1.5$	Moderate drought	$0.6 < TVDI \leq 0.8$
Extreme drought	$SPEI \leq -2.0$	Severe drought	$0.8 < TVDI \leq 1.0$

where S is the drought intensity, m is the number of stations experiencing drought, and $SPEI_i$ is the absolute $SPEI$ value when drought is occurring. The drought frequency is defined as:

$$P = \frac{n}{N} \cdot 100\% \qquad (7)$$

where N is the total number of years, n is the number of droughts, and P is the frequency of drought. Based on the drought classifications, frequency of mild, moderate, severe, and extreme drought could be calculated.

To quantify contribution of each meteorological factor to drought, the method of contribution rate was applied (Li et al. 2014). The impacts of climatic factors on the droughts are independent, and their nonlinear correlations are not considered. The climatic factors and drought indexes were standardized before conducting regression analysis that was conducted. Then, the contribution of climatic factors to drought was calculated as follows:

$$Y = \sum_{i=1}^{n} \alpha_i X_i \qquad (8)$$

$$\eta_i = \frac{|\alpha_i|}{\sum_{i=1}^{n} |\alpha_i|} \qquad (9)$$

where Y is the dependent variable (i.e., drought intensity), X_i is the climatic factor i, α_i is the regression coefficient, and η_i is the contribution of climate factor X_i to Y. As the difference between precipitation and potential ET is mainly controlled by temperature, wind speed, sunshine duration, and vapor pressure, these climate factors were selected to make contribution analysis.

3 Results and discussion

3.1 Temporal and spatial variability of SPEI during periods 1971–2014 over Tibet

Figure 2 illustrates the temporal and spatial variations of SPEI-12M and SPEI-3M at each station over Tibet during the period 1971 to 2014. SPEI-3M of May, August, November, and February represented the dryness/wetness condition of spring, summer, autumn, and winter from 1971 to 2014, respectively. For more than two-thirds of the stations across Tibet, the SPEI-12M presented decreasing trends from 1971 to 2014 (Fig. 2a). In addition, the SPEI-12M of eight stations showed significant decreasing trends ($P < 0.05$) which illustrated most parts of Tibet experienced drying trends during 1971 to 2014 (Fig. 2a). For SPEI-3M, just four and nine stations exhibited increasing tendency for SPEI-3M of November and

May, respectively (Fig. 2b, d), and over one half stations showed increasing variation (Fig. 2c) for SPEI-3M of August (Fig. 2c). Furthermore, all stations' SPEI-3M of February showed decreasing trends (Fig. 2e). As a result, summer and winter were the wettest and driest season and autumn is drier than spring during period 1971 to 2014 over Tibet. In the watersheds of the middle reaches of the Yarlung Zangbo River, its two tributaries and the southeast corner of Tibet drying condition were becoming more severe in consideration of SPEI-12M and SPEI-3M variations. On the contrary, dryness conditions appeared to be alleviated in eastern Shigatse and eastern Naqu for the increasing trends from 1971 to 2004.

3.2 Distribution and changes in drought intensity and frequency over Tibet

Quantifying the inter-decadal variations of drought condition is helpful for forecasting drought occurrence and reducing or avoiding its impacts on agriculture and society. As extreme drought events seldom occur, here, we only analyzed the intensity and frequency of mild, moderate, and severe droughts across Tibet. Drought frequency and intensity were calculated by using 3-month SPEI (SPEI-3M) at 38 meteorological stations.

Figure 3-I–III shows the average intensity of mild, moderate, and severe droughts at the 38 stations and their decadal changes (mean value of $-1 < \text{SPEI-3M} < -0.5$, $-1.5 < \text{SPEI-3M} < -1$, and $\text{SPEI-3M} < -1.5$, respectively). The intensities of mild, moderate, and severe drought ranged from 0.72 to 0.77, 1.12 to 1.27, and 1.63 to 1.93, respectively (Fig. 3-I).

According to SPEI-3M, the intensity of moderate and severe drought changed much larger than that of mild droughts (Fig. 3), which further demonstrated aggravated dryness condition across Tibet from 1971 to 2014. Additionally, intensity of moderate drought appeared to increase in period of 1981–1990 rather than other periods. Similar results were found for severe drought. The intensity of severe drought also showed a substantial increase during 1981–1990 compared with earlier period 1971–1980, and about half the stations' severe drought intensity increased more than 0.1. Therefore, Tibet experienced significant drying conditions during period 1981–1990. Nevertheless, in period 1991–2000, intensity of severe drought exhibited decreasing trends in eastern and southern Tibet. Overall, there were substantial spatial variations of the decadal changes in drought intensity.

Figure 4 depicts the number of mild, moderate, and severe drought occurrence in the 38 meteorological stations across Tibet. Figure 5 displays distribution of drought frequency and the decadal changes in mild, moderate, and severe droughts frequency from 1971 to 2014, respectively. From 1971 to 2014, mild drought occurred 222 times, moderate drought 167 times, severe drought 69 times, and extreme drought 21
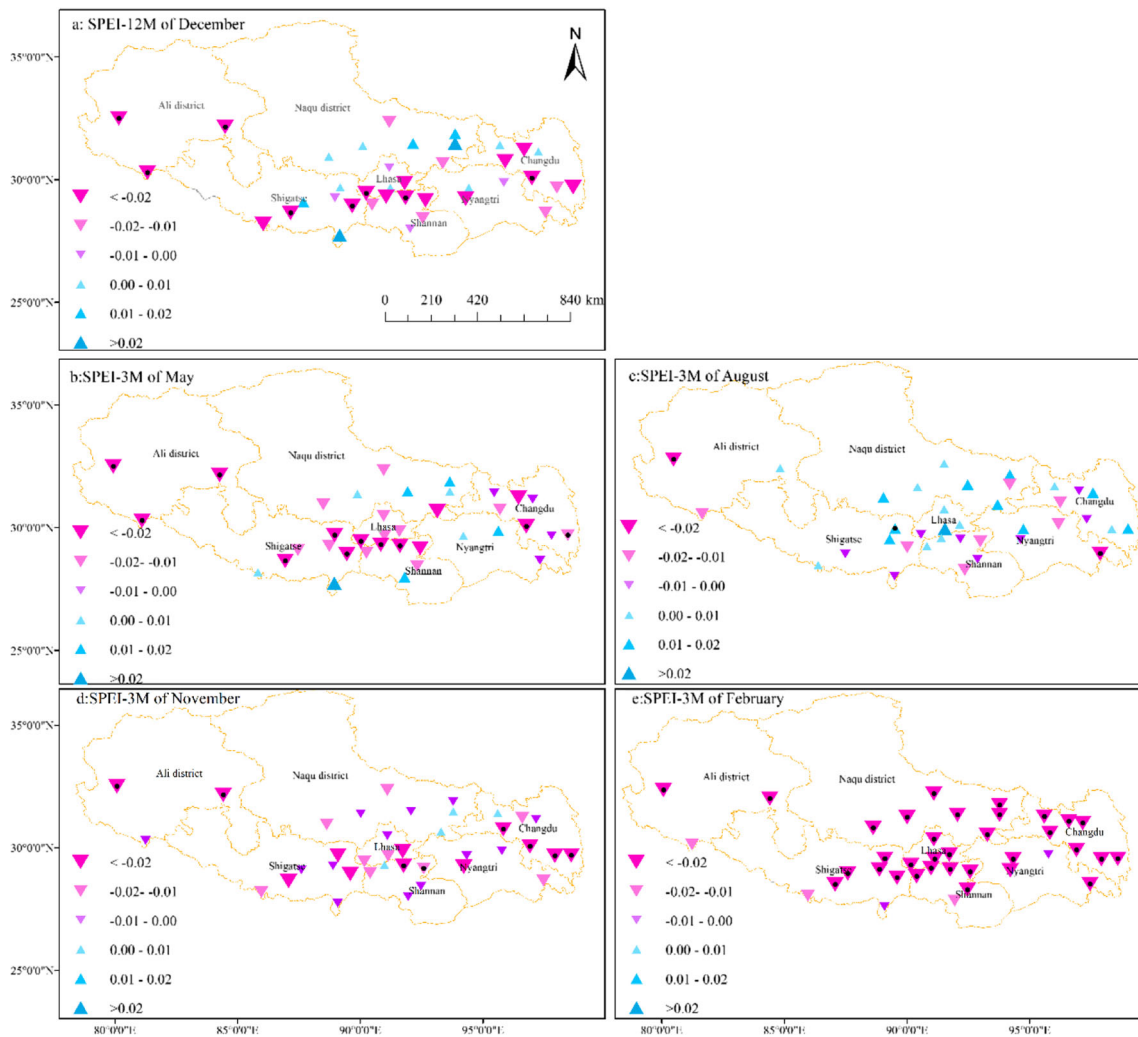
Fig. 2 **a** The trend of SPEI-12M (12-month SPEI) of December. **b** SPEI-3M (3-month SPEI) of May, **c** August, **d** November, and **e** February during 1971–2014. The equilateral triangle indicates increasing trends, and the inverted triangle indicates decreasing trends. The point indicates that the differences are significant at the 95% confidence level based on Student's test

times based on the SPEI-3M value indicating that drought is a common phenomenon across Tibet (Fig. 4). Moreover, mild drought and moderate drought are frequenters over Tibet. Severe drought occurred more frequently in northern stations than in other regions (Fig. 4). The frequency of mild drought ranges from 12.2 to 17.7%, moderate drought from 7.6 to 13.0%, and severe drought from 5.3 to 8.3% (Fig. 5). Frequency of mild, moderate, and severe droughts was all in increase in the period 1981–1990 compared with 1971–1980 especially at the middle reaches of Yarlung Zangbo River and its two tributaries as well as eastern Changdu district which was similar with drought intensity variation (Fig. 5-Ib, -IIb, -IIIb). Furthermore, both frequency of moderate and severe drought showed substantial increase at more than three quarters of stations in the period 2001–2014 compared with 1991–2000 which emphasized more drought events occurred since 2000 (Fig. 5-IId, -IIId). In addition, in the period 1991–2000, frequency of severe drought decreased in eastern and southern

of Tibet which variated similarly with intensity of severe drought.

The above sections analyzed the drying trends, distribution, and decadal variation of drought frequency and intensity across Tibet based on SPEI-12M and SPEI-3M. As illustrated in Figs. 2, 3, 4, and 5, dryness conditions could be found in two-thirds region of Tibet from 1971 to 2014. Dryness/wetness over Tibet was mainly influenced by precipitation which was demonstrated by latter contribution rate analysis. The lack of moisture transported into Tibet results in an arid environment. On one hand, atmospheric moisture, transported into Tibet by prevailing westerly winds, is typically intercepted by the high elevation topography of it (Tian et al. 2003). On the other hand, it is difficult for the water vapor to get in, as Tibet is in the interiors of continents and surrounded by higher mountains. Dryness condition is relatively weak in southeast part of Tibet especially during period 1991–2000, as high precipitation rates have been detected in southern Tibet
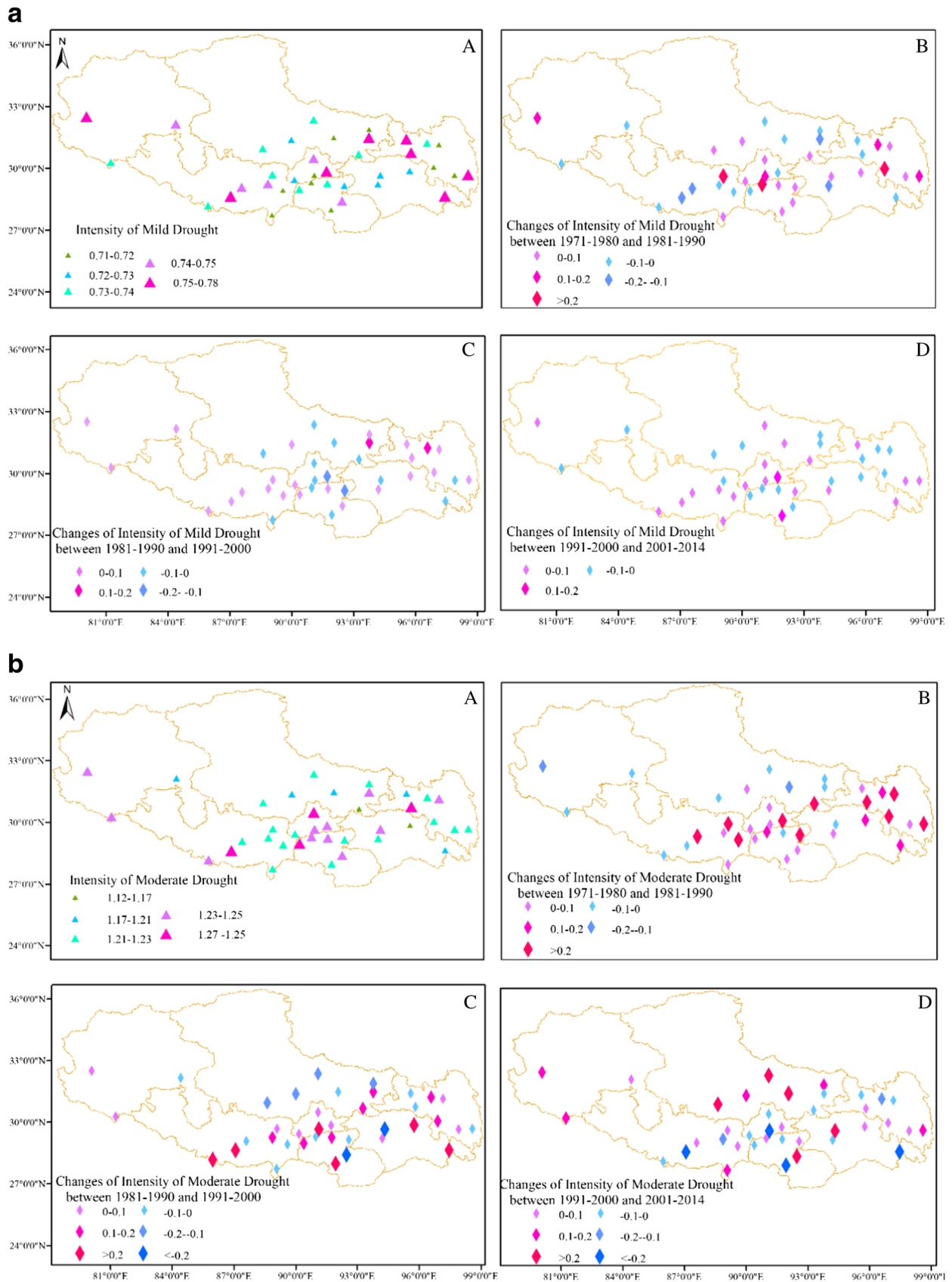
Fig. 3 The average intensities of different droughts during 1971–2014 (A) and the change during various periods: (B) 1981–1990 vs. 1971–1980, (C) 1991–2000 vs 1981–1990, and (D) 2001–2014 vs. 1991–2000. **a** Mild drought. **b** Moderate drought. **c** Severe drought
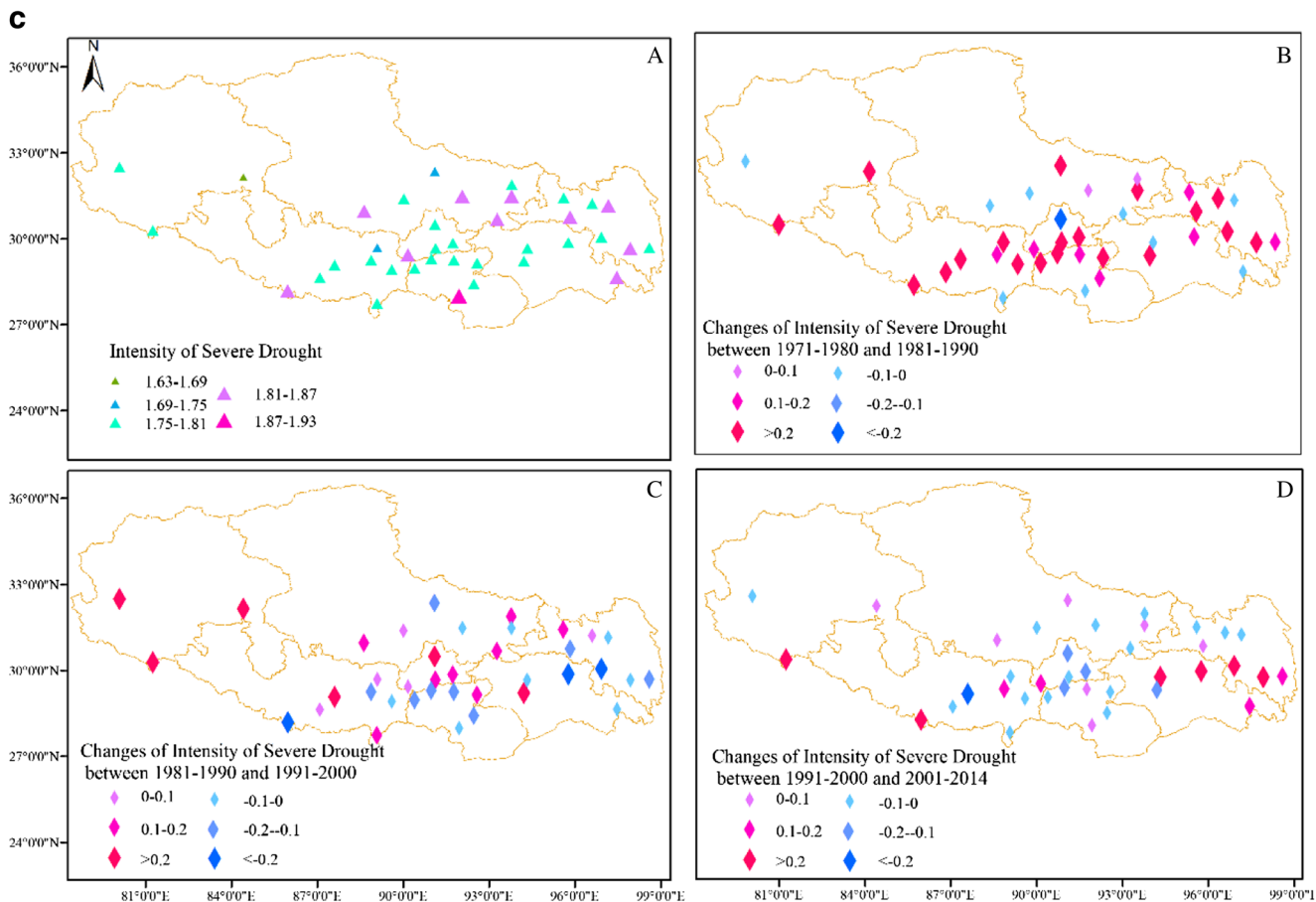
Fig. 3 (continued)

plateau due to the strong monsoon activity (Tian et al. 2003). In recent years (from 2001 to 2014), Tibet was subjected to more drought events which demonstrated extreme events posed by climate change that was increased (Rosenzweig
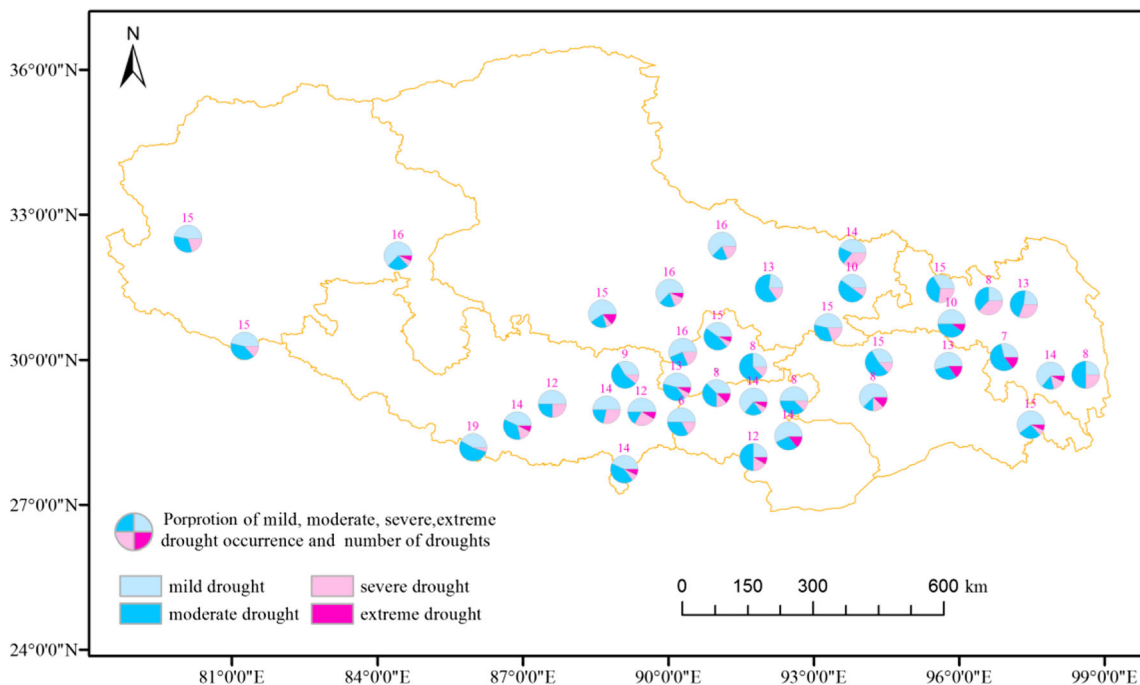

Fig. 4 The estimated occurrences of mild, moderate, severe, and extreme drought during 1971–2014

et al. 2001; Trenberth 2011; Beniston and Stephenson 2004), and we should pay more attention to its impacts on the agriculture and economics and its major causes. Developing a reliable drought monitoring and forecasting system is critical for reducing the impact of drought and increasing the resilience to extreme events.

3.3 Relative contribution of meteorological factors to SPEI-12M

According to observations from 1971 to 2014, Tibet experienced substantial climate change. During this period, annual precipitation and mean temperature showed significant increases with rates of + 12.5 mm per decade ($P < 0.05$) and + 0.6 °C per decade ($P < 0.01$), respectively. Meanwhile, the annual average relative humidity, average wind speed, and sunshine duration decreased with rates of − 0.04 per decade, − 0.3 m/s per decade ($P < 0.01$), and −20.3 h per decade ($P < 0.01$), respectively.

Figure 6 depicts the contribution of these five meteorological factors to SPEI at each station. Annual precipitation was the dominant factor controlling SPEI at these stations with relative contribution over 50% except for Shiquanhe where relative contribution is 27% (Fig. 6). At 10 stations in Northwest of Tibet, contribution of wind was more than 20% to the variations of SPEI and was higher than that of sunshine duration; in particular, its contribution was larger than that of precipitation at the Shiquanhe station. Opposite results were found in Southeast. Contribution of wind speed was lower than that of sunshine duration who contributed more than 15% to the variations of SPEI for the 13 stations in the region. Overall, precipitation acted the most significant role in view of variation of SPEI, followed by sunshine duration, wind speed, and temperature, and relative humidity was the least contributing factor to SPEI variation. Tibet is distinguished from other regions because of its diversity in meteorological and topographical units. As a result, the contribution of meteorological factors to SPEI has large spatial variations (Fig. 6).

Drought occurrence mainly depends on the difference between precipitation and evapotranspiration which is the result of comprehensive effects of various meteorological factors (Li et al. 2014; Xu et al. 2017; Zhang et al. 2007). This study suggested that precipitation, sunshine duration, and wind speed were the dominant factors controlling the occurrence of drought and its intensity over Tibet. In general, when water supply is adequate, temperature would act an important role in evapotranspiration variation which indicates the significant effects of temperature to droughts. However, the temperature of Tibet is lower compared with the adjacent area, and the air could hold smaller amount of water vapor. So, it would have insignificant influence on evapotranspiration. As a result, it is obvious that the effects of temperature to drought are exceedingly weak in Tibet. Moreover, from 1971 to 2014, variation quality of annual average temperature is smaller than that of sunshine duration and

wind speed duration according to the standardized value which leads to the lower relative contribution of temperature to drought. This study also demonstrated that the contribution of wind speed was larger than that of sunshine duration in the northwest. However, over southeast of Tibet, the results were inverse. This is also closely related to variation quality of meteorological factors. From 1971 to 2014, variation quality of wind speed of 1.63 is bigger than that of sunshine duration of 0.77 according to the standardized value in northwest and in southeast variation quality of the sunshine duration which is larger.

The characteristic and influencing factors of dryness across Tibet were different compared with other regions of China (Wang et al. 2014, 2015; Li et al. 2017b; Lou et al. 2018). For instance, in southwest of China, the dryness condition is mainly due to the enhanced rate of potential evapotranspiration higher than that of precipitation (Wang et al. 2014). In contrast, over Tibet, the potential evapotranspiration was decreasing and it was the insufficient precipitation dominantly leading to the dryness environment (Zhang et al. 2007). The unique geographical unit of Tibet thus made it quite distinctive from other regions.

3.4 Comparison of the SPEI and TVDI for monitoring drought over Tibet

Throughout Tibet, the number of meteorological stations is so limited that only using these observational data might bring huge uncertainty in characterizing dryness condition. Therefore, in this study, we used two drought indexes—TVDI and SPEI—which allowed us to integrate satellite and observed meteorological data in quantifying drought events. The time series of TVDI-16D and SPEI-16D from 2001 to 2014 indicated that Tibet experienced frequent alternation of wet and dry phases and this was also verified by the variation of drought frequency according to SPEI-3M during periods 2001–2014. After 2009, Tibet has been becoming mildly wetter with decreasing TVDI-16D and drought intensity based on SPEI-16D values which agreed with the Southern Tibetan Plateau and the Northwest of China (He et al. 2011; Wang et al. 2017).

Since the values of TVDI and SPEI have different drought scales and signs, they were standardized before this comparison. Both TVDI-16D and drought intensity derived from SPEI-16D showed decreasing trends after 2009. However, the decreasing trends of TVDI-16D and drought density based on SPEI-16D were disagreement with each other; for example, TVDI-16D and drought density based on SPEI-16D detected abrupt decrease in 2012 and 2014, respectively (Fig. 7a). Based on the strength of drought area of 2014, the SPEI-16D performed better than TVDI-16D did. Moreover, both TVDI-16D and drought density based on SPEI-16D detected moderate droughts in 2009 and 2010. Surveyed drought area from the Department of Plantation, Ministry of Agriculture, also confirmed that there were striking droughts in 2009 and 2010 on account of the drought areas in 2009 of
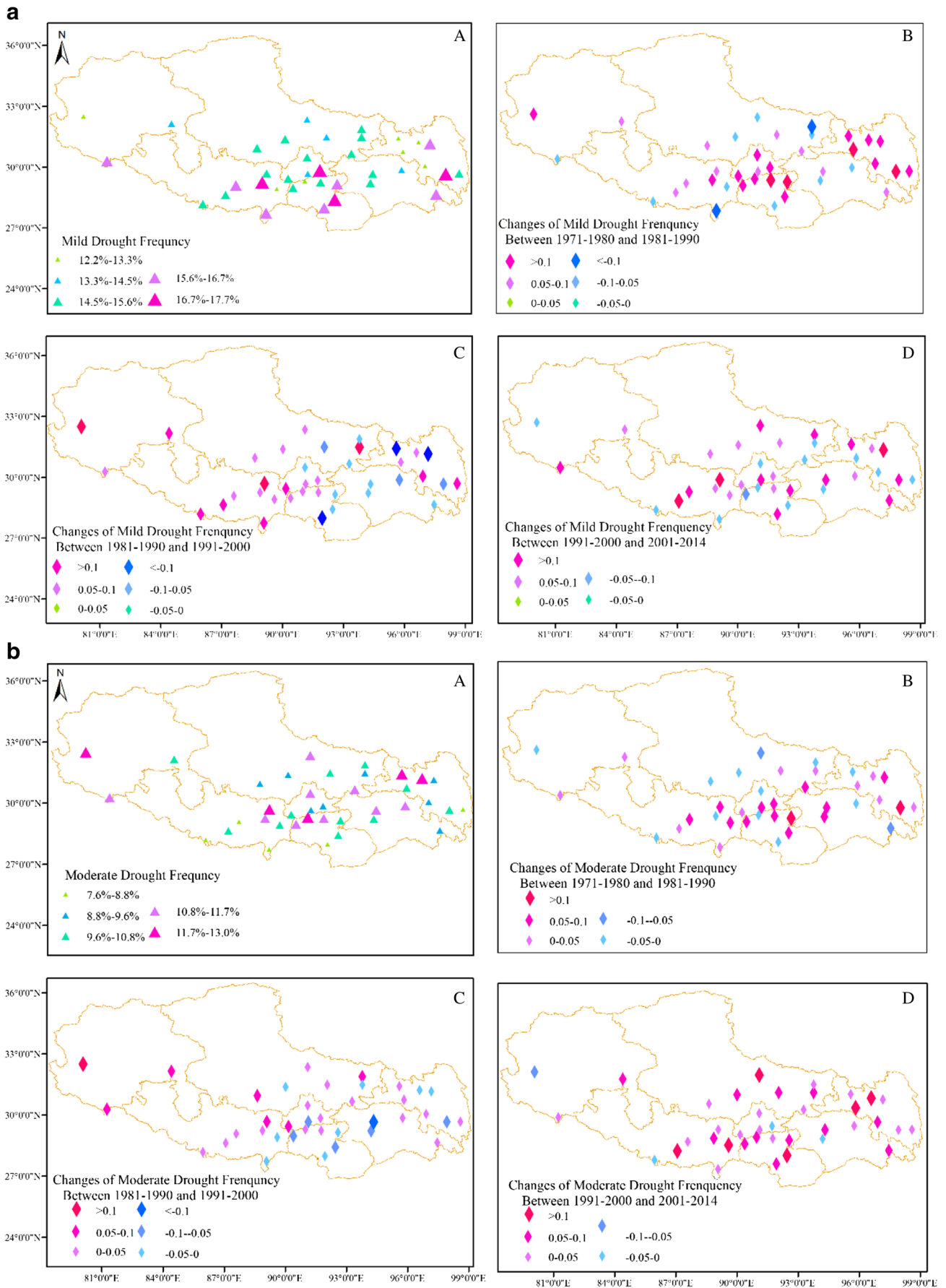
Fig. 5 The average frequencies of different droughts during 1971–2014 (A) and the change during various periods: (B) 1981–1990 vs. 1971–1980, (C) 1991–2000 vs 1981–1990, and (D) 2001–2014 vs. 1991–2000. **a** Mild drought. **b** Moderate drought. **c** Severe drought

27,000 km^2 and 2010 of 40,300 km^2. Throughout the overlapping period of 2001 to 2014, the Pearson's correlation coefficient of these two indexes was only 0.31. TVDI-16D had the similar variation tendency to the drought intensity based on SPEI-16D from 2001 to 2014, but there were still differences between TVDI-16D and drought density based on SPEI-16D.

Figure 7b, c illustrates the spatial variation in TVDI-16D and SPEI-16D from 2001 to 2014, respectively. The TVDI-16D in the northwest, southwest, and part of the southeast displayed trend of wetting; over the central and south-central regions, TVDI showed trend of drying. The wetting area accounted for 52.2% of the Tibet area, which was slightly larger than the drying area. The trends of SPEI-16D of the meteorological stations in southwest Pulan, Neilaer, and southeast regions of Cuona, Linzhi, and Basu showed positive values, which indicated that these regions were becoming wetter (i.e., less drought). Figure 7b, c reveals that drought

information from these two indexes are mostly consistent over spatial distributions.

In a word, temporal and spatial covariation of TVDI-16D and SPEI-16D from 2001 to 2014 compared with drought area demonstrated that the two indexes could efficiently monitor dryness condition. Combined using TVDI and SPEI brought detailed information about drought condition variation across Tibet which could be important references for policy-makers to arrange reasonable agricultural activities and develop drought prediction system. Furthermore, some disagreements did occur between the TVDI-16D and SPEI-16D variations. For example, the higher TVDI (more severe drought) normally occurs from day-of-year (DOY) 273 to DOY 33 of the following year (mainly in winter). However, according to SPEI, more severe drought (i.e., the lower SPEI) normally occurs from DOY 97 to DOY 177 (mainly in spring) (Fig. 8). The seasonal difference in estimated drought severity between these two indexes is caused by their different input variables; SPEI uses precipitation and potential ET, while TVDI uses temperature and NDVI. In winter season, NDVI is low because of the inactivity of vegetation, which results in high TVDI (i.e., more severe drought). Conversely, in spring, the NDVI is returning to high value, which will increase TVDI, hence indicating decreased drought
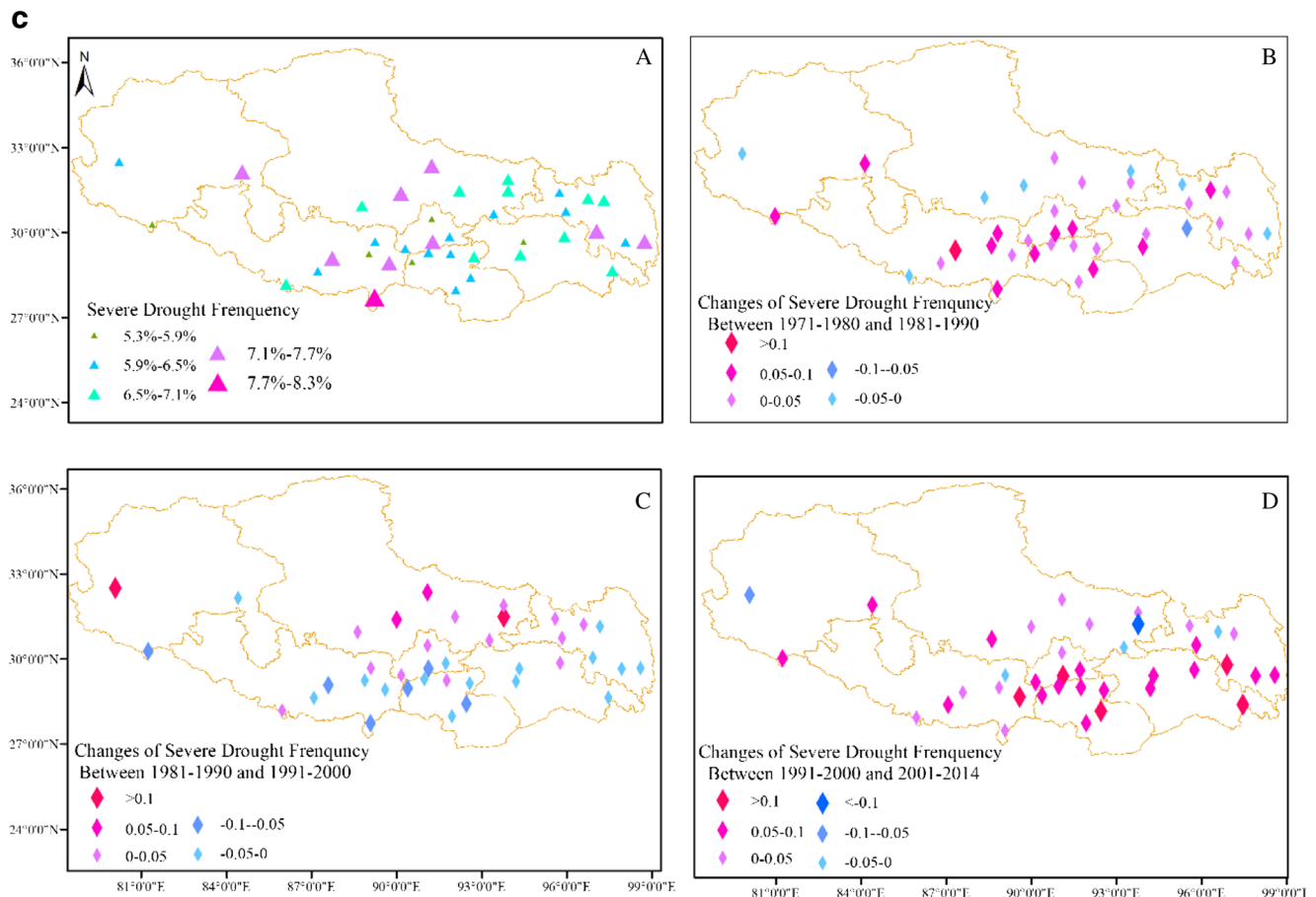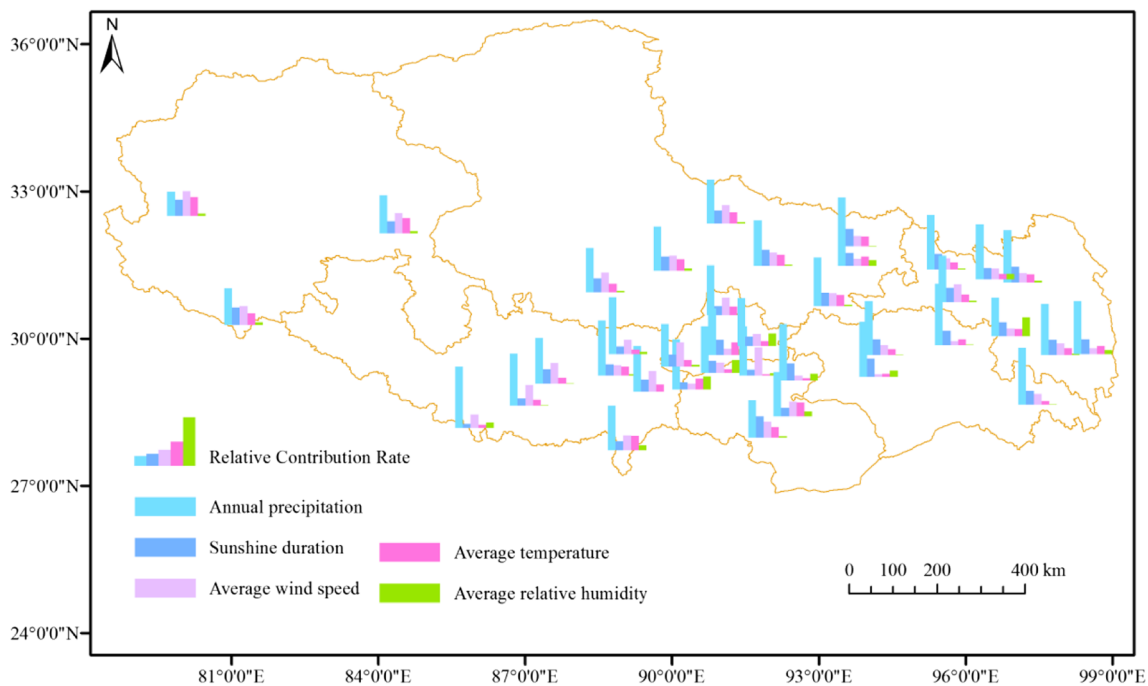

Fig. 5 (continued)

Fig. 6 Relative contributions of meteorological factors to the drought index (SPEI-12M)

intensity. As to SPEI, PET is higher in warmer seasons. Moreover, the rainfall in the period of DOY 97 to DOY 177 was lower than the rainfall in summer. Therefore, the difference between precipitation and PET is the lowest in this period, which led to estimated severe drought.

ET and precipitation are two dominant meteorological processes controlling the occurrence and severity of drought (Wilhite and Glantz 1985; Dai 2013). The difference between ET and precipitation has been widely used as drought index inputs (Vicente-Serrano et al. 2010). However, given the difficulty in obtaining actual ET, this data is generally replaced with potential or reference ET, which may introduce some uncertainties in estimating or forecasting drought occurrences. SPEI takes potential ET as an input variable, so some uncertainty will exist in the drought value. The inputs for calculating TVDI are all from remotely sensed data, which represent the condition of land surface and vegetation cover. However, effects of topography and clouds may introduce missing data and uncertainty to TVDI-derived drought assessment. In recent decades, the frequency of droughts has increased, while its impacts are seldom assessed; therefore, developing new methods to retrieve historical drought events could help us in better understanding the spatio-temporal patterns of drought and forming drought-relief strategies.

4 Conclusions

In this study, drought condition, variation in meteorological drought intensity and frequency, and comparison

between TVDI and SPEI were investigated based on multiple data sources (meteorological data from 38 station, MOD13A2 and MOD11A2) from 1971 to 2014 over Tibet. We found that most parts of Tibet experienced drying trends from 1971 to 2014, as more than two-thirds of the stations' SPEI-12M presented decreasing trends. Drought intensity and frequency exhibited substantial decadal variations with higher intensity drought events occurring in the period 1981–1990 and more frequent drought occurring during period 1981–1990 and since 2000 based on SPEI-3M across Tibet. Compared with other regions in Tibet, watersheds of the middle reaches of the Yarlung Zangbo River and its two tributaries experienced more drought events and stronger drying trends from 1971 to 2014. In addition, factor analysis revealed that precipitation, sunshine duration, and wind speed contributed predominantly to drying/wetness variation from 1971 to 2014. The pattern and influencing factors of dryness across Tibet were different with other regions of China, and it may be due to the unique geographical unit of Tibet. Comparison between SPEI and TVDI from 2001 to 2014 by means of drought area data demonstrated the high effectiveness of the two indexes in monitoring drought event, and in terms of temporal variation of dryness/wetness condition, SPEI outperformed TVDI.

Under the context of climate change, the frequency and intensity of drought events will change over time and spatial domains. To enhance the capability of forecasting drought events and subsequently eliminate their impacts on crop and livestock production, using proper drought indexes and
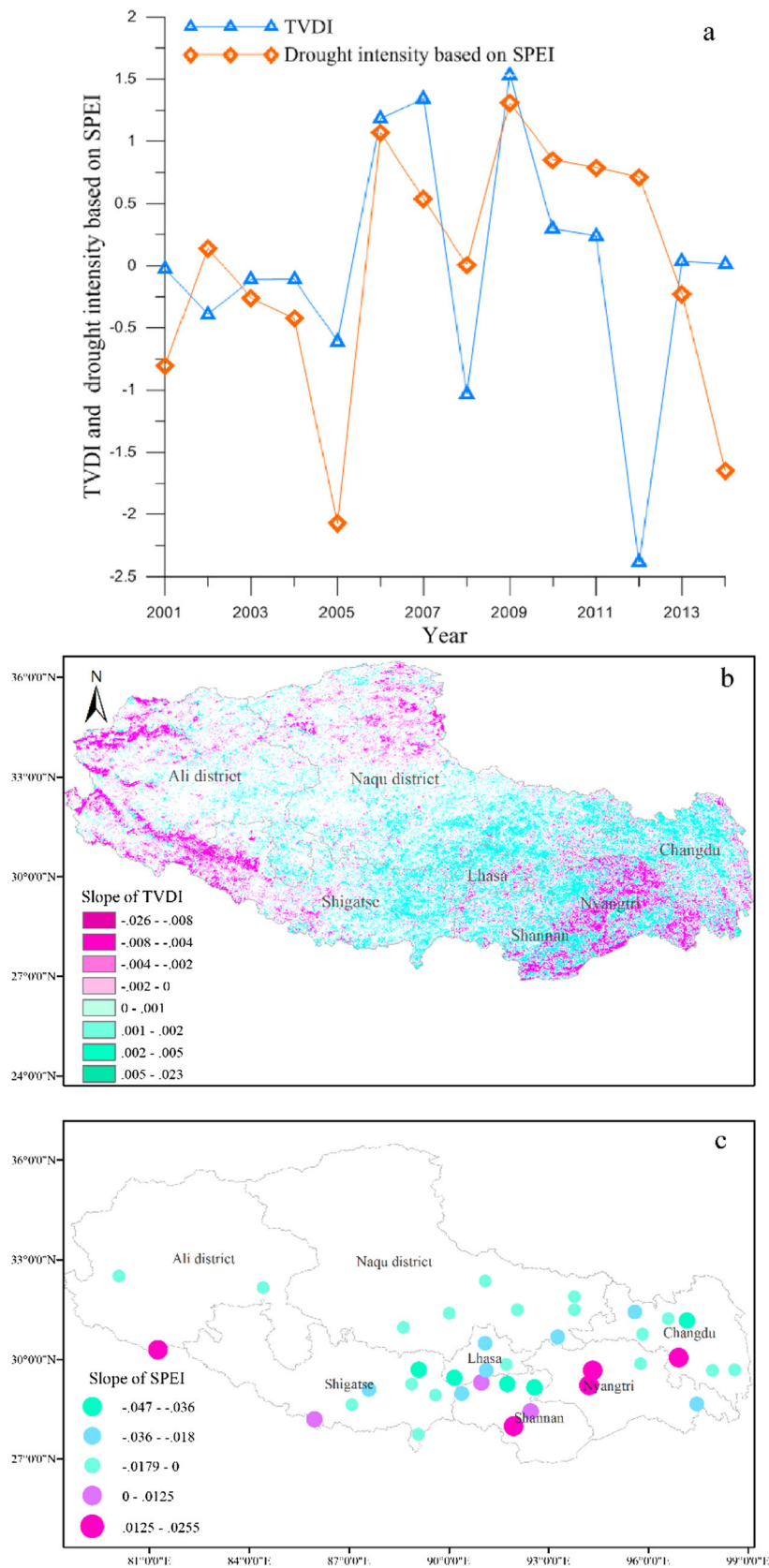
Fig. 7 Comparisons between TVDI and SPEI. **a** Inter-annual variations of TVDI and the drought intensity estimated from SPEI. **b** The trend of TVDI-16D. **c** The trend of SPEI-16D
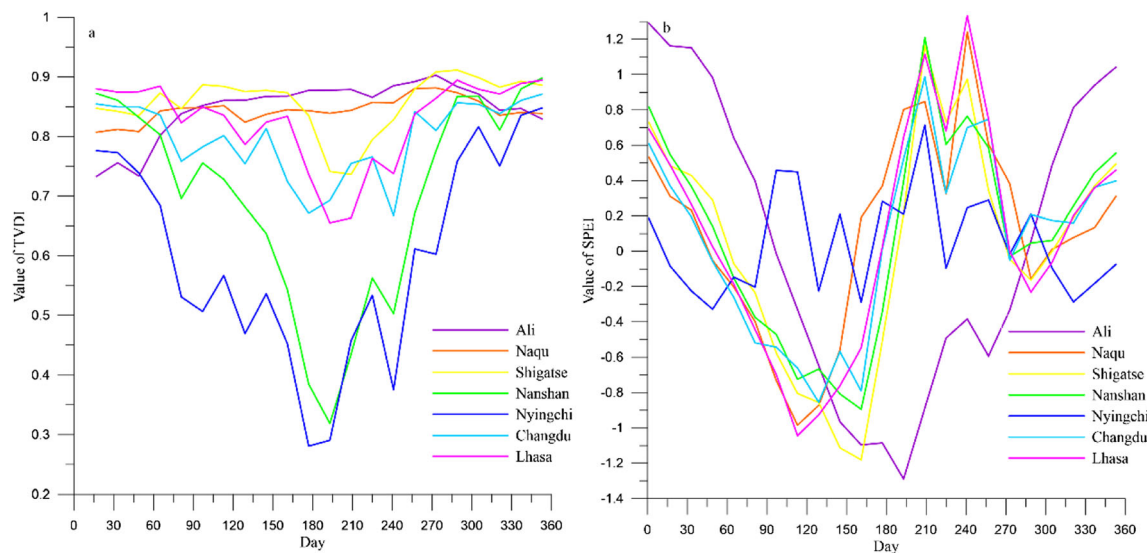
Fig. 8 Comparisons between TVDI-16D and SPEI-16D in annual variations. **a** Annual variation of TVDI-16D; **b** Annual variation of SPEI-16D

multiple sources of data is helpful for characterizing drought over historical periods. Meteorological and agricultural drought detected with SPEI and TVDI, respectively, were analyzed in this study; other types such as hydrological drought and snowpack drought should be studied further for finding the cause of drought and its consequences to streamflow and downstream river basins. Therefore, investigating the relationship between drought and other processes in the hydrological cycle should be prioritized. In the context of global warming, the snow-melt runoff for many rivers in most parts of the world has shifted to earlier in the season (McCabe and Clark 2005; Moore et al. 2007; Clow 2010), and the effective snow-melt volume is estimated to decrease in the future (Islam et al. 2017; Li et al. 2017a). Quantifying the impact of this change—in particular, connections with snow and hydrological drought occurrence and intensity—is important. Future studies should investigate the relationship between drought and the hydrological process; this will be beneficial for identifying variations in the hydrological cycle and act as references for water resource management.

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