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# Change of summer drought over China during 1961–2020 based on standardized precipitation evapotranspiration index

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## Abstract

With the aggravation of climate change, drought has become a more prominent extreme event with serious consequences. The selection of drought indices is crucial for accurate quantification and assessment of drought change and its impacts. In this study, we first evaluated the standardized precipitation evapotranspiration index (SPEI) at different time scales in terms of their applicability to reflect changes in summer drought over China through comparison with observation-based drought indices including soil moisture (SM) dataset. We found that precipitation and SM both exhibit a drying feature from northeastern China to southwestern China. At different time scales, the 1-month SPEI (SPEI-01) has the best performance in reflecting the changes of summer SM over China. Using SPEI-01, we examined the spatial pattern of change in drought intensity and frequency from 1961 to 2020 in China at a national scale and further compared drought change in regions with different aridities. Overall, China witnessed a wetting trend in the past 60 years. Arid and semiarid regions were featured with "dryer in the east and wetter in the west." A drying trend was found in the southeast of the Tibetan Plateau and Beijing-Tianjin-Hebei region. In humid regions, drought relieved in the Yangtze River Delta but worsened in the southwest of China. Changes in drought frequency and intensity also exhibited remarkable spatial heterogeneity. Our results can contribute to a better understanding of the spatial-temporal variations of drought severity for climate change adaptation.

## 1 Introduction

Drought, as one of the most significant extreme climate events in the world, has well-recognized influences on terrestrial ecosystems, water storage, human life, production and development, and social stability (Wilhite 2000; Mishra and Singh 2010; Huang et al. 2020; Pokhrel et al. 2021; Vogt et al. 2021). *The Flood and Drought Disaster Bulletin* records drought events each year, reporting that drought has caused huge economic losses in China (Su et al. 2018). According to the Special Report on Global Warming of 1.5 °C, drought concerns have received more attention in recent years due to the increasing drought frequency and/or severity (Spinoni et al. 2020; Vogt et al. 2021). Under high emission scenarios by 2100, extreme drought may become

a regular climate condition in mid-to-high latitudes (IPCC 2013, 2021). China, with typical monsoon climate, has been frequently affected by droughts (Zhang et al. 2015, 2019). Therefore, drought monitoring, change study, and projection are critical for the impact of drought on China.

Drought indices have been developed for drought monitoring, diagnosis, and projection. Based on previous researchers focusing on the sensitiveness and suitability of the drought indices, several indices have considerably evolved in recent decades (Mishra and Singh 2010; Mukherjee et al. 2018). Standardized precipitation evapotranspiration index (SPEI) is a widely used drought index in previous researches that has analyzed drought variability, climate change, and identification of drought impacts on agricultural and ecological systems (Begueria et al. 2010; Cao et al. 2022). Various types of droughts emphasize differences in duration in their definition, and previous study has been suggested that SPEI with different time scales can generally represent different drought types (Potop et al. 2012; Begue-ría et al. 2014; Yao et al. 2018a; Mukherjee et al. 2018). On the one hand, SPEI combines the advantages of standardized precipitation index (SPI) with multiple time scales and Palmer Drought Severity Index (PDSI) with multifactorial

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consideration. On the other hand, Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith algorithm replaces Thornthwaite algorithm to calculate evapotranspiration in SPEI, which optimizes SPEI to better reflect the real drought condition and the impact on vegetation (Vicente Serrano et al. 2013). Moreover, because of its temporal flexibility, spatial continuity, and water deficits at multiple time scales, SPEI is ideal to reflect the characteristics of drought; as a result, it has become an important instrument for assessing moisture conditions (Potopová et al. 2015; Li et al. 2015; Labudová et al. 2017). Yao et al. (2018b), for instance, used four drought indices to analyze the spatial-temporal evolution of drought in China from 1961 to 2013 and indicated that the drought was tending to alleviate. Based on the comparison of historical drought events, their results further confirmed the applicability of SPEI in identifying continuous drought. Wu et al. (2020) investigated the changes in SPEI in major regions of China on the 1-month and 12-month scales. The results revealed that the fluctuation of SPEI decreases with the increase of time scales. Xu et al. (2021) used three drought indices, soil moisture (SM), and terrestrial water storage to analyze the trend and correlation of drought indices and hydrological variables in different seasons in climatic zones. They showed that SPEI has better performance on agricultural drought in summer. Other studies also tried to quantify the impact of historical drought events based on SPEI (Li et al. 2019; Anderegg et al. 2020).

Other commonly used indices are also used in China for drought change research. For example, Wang and Zhai (2003) used China Z indices to analyze the drought changes in northern China from 1950 to 2000. Zhai et al. (2010) analyzed the drought changes in ten regions of China from 1961 to 2005 based on PDSI and SPI. Their study solely analyzed the trend without considering other characteristics of drought. Although SPI is a valuable index of meteorological drought, however, it only uses precipitation as a single variable to reflect drought (Keyantash and Dracup 2002). PDSI still has inaccuracies in the study of all precipitation treated as rainfall (Hayes 2006). Previous studies analyzed distribution characteristics and disaster change of drought in China using meteorological drought composite index (MCI) (Liao and Zhang 2017). It should be noted that MCI focuses mostly on meteorological conditions and has relatively poor performance on agriculture and hydrology. Yang et al. (2017) assessed the regional applicability of seven drought indices and investigated changes in drought in the Northeast Plain, North China Plain, and Huanghuai Plain using land water storage, in situ SM, and runoff data retrieved by GRACE. Unfortunately, the research area of the study failed to cover the entire China because of low resolution of the observed data. Overall, there still lacks a synthesis of drought severity as well as its spatiotemporal variations over China based on the most applicable drought indices. Few studies have assessed the current drought indices via comparison with observation-based results.

SM is a critical physical quantity for regulating the water cycle, as well as the primary water supply in the ecosystem (Li and Ma 2012). SM anomaly can accurately represent the regional dry-wet conditions and can be used as an objective index to characterize droughts. Thus, it has been widely used to evaluate the accuracy of other drought indices (Sims et al. 2002; Vicente-Serrano et al. 2012). Plenty of studies have suggested that SM is an effective indicator of agricultural and ecological drought. Change in SM has a significant impact on the exchange of energy and water between land and atmosphere (Wang et al. 2009, 2011; Khong et al. 2015). Precise SM data can help us better comprehend climate change and land-atmosphere interaction (Song et al. 2007; Seneviratne 2010). The constraint and uncertainty of datasets, particularly for SM, are one of the main challenges to detecting long-term changes in drought (Trenberth et al. 2014; Beguería et al. 2016; Dai and Zhao 2017). SM data based on in situ observations has the disadvantages of small spatial scale and lack of data, while SM data based on model simulation is difficult to reflect the real situation (Busch et al. 2012; Crow and Ryu 2009). With the development of remote sensing technology, SM based on satellite observations has been widely used in drought investigation since the 1970s. Through evaluation of multiple resource datasets, related studies suggest that the European Space Agency Climate Change Initiative (ESA CCI) SM dataset (Dorigo et al. 2017) is generally credited for change of SM in different seasons over China (Peng and Loew 2017; An et al. 2016; Ma et al. 2016). The latest research thoroughly evaluated the applicability of different datasets (satellite-based and reanalysis products) over China in conjunction with in situ SM (Ling et al. 2021). It showed that ESA CCI SM products were closest to the observed values in terms of spatial distribution and monthly humidity, indicating that the products were a solid choice for long-term hydrological application in China. As a result, on the basis of having high-resolution SM data, it is helpful to compensate for the lack of research about drought caused by insufficient data.

Previous studies concentrated on drought trend change in inter-indices assessment and the link between SPEI and vegetation indices or the response of vegetation to drought in China. Thus, the primary objective of this study is to investigate the change in drought severity in China during the past six decades. We aim to (Anderegg et al., 2015) assess the applicability of SPEI at different time scales based on their relationship with observation-based SM dataset, (Anderegg et al., 2020) explore the spatial pattern of change in the intensity and frequency of summer drought during the past six decades across China, and (An et al., 2016) reveal the regional variations of change in drought intensity and

frequency. The findings of this study could deepen our understanding on changes in drought characteristics in China, provide a scientific basis for studying the impact of extreme drought events in the context of climate change, and serve as scientific guidance on drought risk management in China.

## 2 Data and methods

### 2.1 In situ datasets

The in situ surface daily dataset including maximum temperature, minimum temperature, precipitation, sunshine duration, wind speed, pressure, and relative humidity, from 1961 to 2019 of 2481 meteorological stations in China was applied to calculate drought indices. The data can be found from the National Meteorological Information Center of China Meteorological Administration (http://www.nmic.cn/). In this study, totally 1278 stations were selected through the following criteria: (i) the horizontal relocation distance of the station did not exceed 20 km, and the vertical height change does not exceed 50 m; (ii) the amount of missing data at each station does not exceed 5% of the total amount in the selected period.

The 10-day in situ SM from 115 stations from 1992 to 2012 is also from the National Meteorological Information Center of China Meteorological Administration (http://www.nmic.cn/). According to station information matching and missing values elimination, 111 stations were selected for the evaluation of ESA CCI SM data.

### 2.2 Gird datasets

SM data based on satellite observation from ESA covering from 1979 to 2019 (https://www.esa-soilmoisture-cci.org/) was used in this study. The temporal resolution of this dataset was daily, and the spatial resolution is $0.25° \times 0.25°$ (Hollmann et al. 2013). Note that in this study, we assumed that SM is the true reflection of the surface drought conditions.

### 2.3 Drought indices

We used SPEI to analyze the trends, duration, severity, and spatial distribution of drought during 1961–2020. The gridded SPEI dataset (SPEI base v.2.7; https://digital.csic.es/handle/10261/268088) was at a 0.5° spatial resolution and monthly time step (Vicente-Serrano et al., 2010a, 2010b; Beguería et al. 2022). It was noted that the calculation of the potential evapotranspiration in datasets is based on the FAO-56 Penman-Monteith method (Beguería et al. 2022). We selected 1-month (SPEI-01), 3-month (SPEI-03), 6-month (SPEI-06), and 12-month SPEI (SPEI-12) in our study. In situ drought indices (SPI, SPEI, PDSI, and MCI) are also calculated in this study for robust test. Related concepts and principles for drought indices were as shown in Table 1.

For the formula of MCI, $SPIW_{60}$ is 60-day standardized weighted precipitation index, $MI_{30}$ is 30-day moisture index, and $SPI_{90}$ and $SPI_{150}$ are 90-day and 150-day standardized precipitation index. Among methods to calculate potential evapotranspiration (PET), FAO Penman-Monteith algorithms were used in this study (Penman 1948).

In this study, daily drought indices (SPI, MCI, SPEI, PDSI) were calculated and processed as monthly data. Moreover, annual data was obtained from monthly data by arithmetic average to analyze the change in drought condition.

### 2.4 Statistical analysis

We calculated the missing rate of ERA CCI SM in different seasons in China as shown in Fig. S1. It shows that the missing rate mostly maintains below 20% in summer except for the years of 1988, 1989, 1990, 2003, and 2004 while above 50% in winter. This suggests that analyses focusing on summer as the research period bring the least uncertainties to the major conclusion. Thus, in this study, summer drought was assessed, which was defined as June to August. In situ

**Table 1** Drought index concept table

| Index | Principle | Algorithm | Reference |
|---|---|---|---|
| SPI | It is assumed that precipitation obeys $\Gamma$ probability distribution | $F(x) = \frac{1}{\beta^\gamma \Gamma(\gamma)} x^{\gamma-1} e^{-x/\beta}$ | McKee et al. (1995) |
| SPEI | Calculating the difference between P and PET and using the log-logistic probability distribution | $F(x) = \left[ 1 + \left( \frac{\alpha}{x-\gamma} \right)^\beta \right]^{-1}$ | Vicente-Serrano et al. (2010a) |
| PDSI | Principle of water balance | $P$ (precipitation) $= ET$ (evapotranspiration) $+ R$ (soil water supply) $+ RO$ (runoff) $- L$ (soil water loss) | Palmer (1965) Zou et al. (2005) |
| MCI | Multiple drought index | $MCI = Ka \times (a \times SPIW_{60} + b \times MI_{30} + c \times SPI_{90} + d \times SPI_{150})$ | Liao and Zhang (2017) |

**Table 2** Drought classification based on SPEI value

| Drought level | SPEI |
|---|---|
| Normal | −0.5 to 0.5 |
| Mild drought | −1.0 to −0.5 |
| Moderate drought | −1.5 to −1.0 |
| Severe drought | −2.0 to −1.5 |
| Extreme drought | ≤ −2.0 |

drought indices were calculated by monthly data and finally processed as seasonal indicators the same as gridded datasets. The gridded SM were resampled to match the spatial resolution of gridded SPEI by using bilinear interpolation. Trends in the precipitation, SM, and drought indices were estimated by using the Mann-Kendall trend test method with the significance level. We then calculated the Pearson correlation coefficients of drought indices with SM, and the Student's $t$-test was used for the significance test. And the impact of missing values was taken into account when calculating trends and correlation coefficients. The root mean square error (RMSE) was used for data evaluation.

We analyzed the changes in summer drought across China from 1961 to 2020 in terms of its intensity and frequency. To this end, for each gird, drought intensity was indicated by the magnitude of SPEI values as shown in Table 2. The cumulative frequency of drought is defined as the number of SPEI values on unit grid meeting the given threshold (i.e., the occurrence of drought events) within a certain period. And the cumulative frequency of drought was used to reveal the regional characteristics of drought occurrence. According to the annual precipitation of in situ observation from 1961 to 1990, China is divided into four regions, arid regions (annual precipitation is less than 200 mm), semiarid regions (annual precipitation is between 200 and 400 mm), semi-humid regions (annual precipitation is between 400 and 800 mm), and humid regions (annual precipitation is more than 800 mm). Changes in drought intensity and frequency were compared between different regions.

## 3 Results

### 3.1 Precipitation change and soil-moisture-based drought change

This study selected the grid nearest to the station for analysis and comparison, as shown in Fig 1. The results show that despite some deviations, the ESA CCI SM data can effectively reflect the characteristics reflected by the in situ SM, with a correlation coefficient of about 0.6 ($p < 0.01$) and an RMSE of 0.07. Therefore, this dataset has the ability to reflect the changes of SM in summer in China.
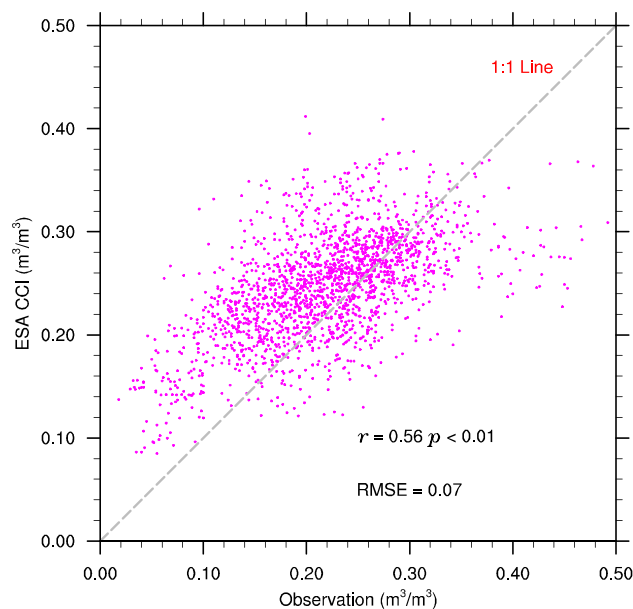


**Fig. 1** Density scatterplots of SM from 1992 to 2012 based on observation and ESA CCI

Figure 2 depicts changes in in situ observed precipitation and satellite-retrieved SM in summer over China from 1979 to 2019. Increased summer precipitation during the past 40 years is observed in the middle and lower Yangtze River, the coastal areas of South China, the Shandong Peninsula, part of the northwestern China, and part of the Tibetan Plateau. In addition to the fundamental characteristics of "southern floods and north droughts" (Zhai et al. 2005), precipitation decreases from northeast to southwest China.

During the last 40 years, SM has increased in most parts of China but decreased mainly in Tarim Basin, Central Inner Mongolia, southwestern Gansu, western Sichuan, and eastern Tibetan Plateau (Fig. 2). Generally, the spatial distribution of summer precipitation trend is generally consistent with SM, in spite of a slight deviation in central China (Fig. 2). This further validates the ability of ESA CCI SM product to reflect spatiotemporal variations of SM in China. Therefore, we used SM from ESA CCI as the actual reference to reflect dry/wet conditions in China in the following analyses.

### 3.2 Assessment of the applicability of SPEI of different time scales

The correlation analysis between summer-gridded SPEI with four different time scales and SM is shown in Fig. 3. Generally, similar spatial patterns are found for SPEI with different time scales regarding their correlation coefficients with SM. High correlation between SPEI and SM is mainly located in the northwest, northeast, North China, eastern
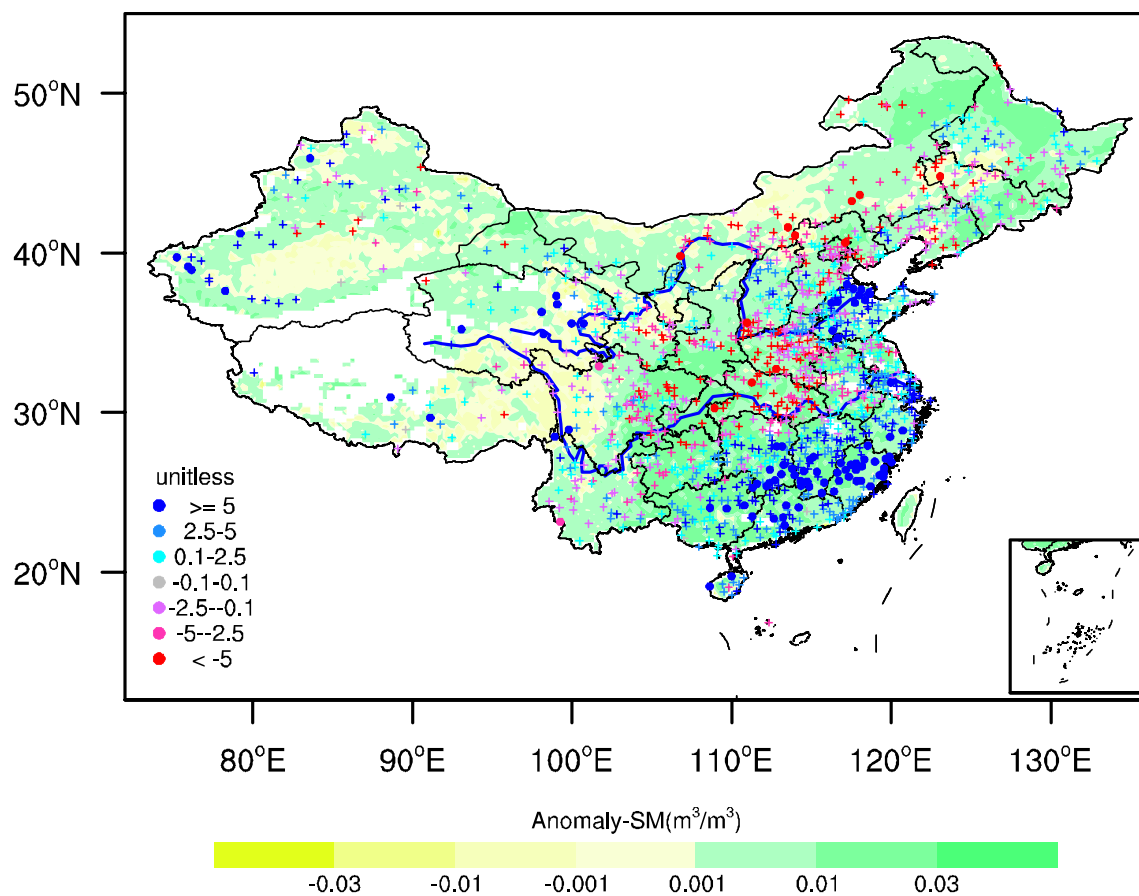
**Fig. 2** Change of precipitation anomaly percentage and anomaly percentage of SM during the period of 1979–2019 in China. Solid color dots indicate trends significant at 95% confidence level. Crosses indicate trends are not significant

Tibetan Plateau, and parts of the south China. However, the correlation coefficients between SPEI-01 and SM are generally higher than that of SPEI-03, SPEI-06, and SPEI-12 across the study regions. Furthermore, for SPEI-01, SPEI-03, SPEI-06, and SPEI-12, the proportion of areas with R values significant at 95% confidence level is 66%, 61%, 47%, and 39% of the research area, respectively. The results indicate that SPEI-01 is more reliable than other time scales in reflecting SM changes in summer. Therefore, in the following study, we utilized SPEI-01 to analyze changes in summer drought in China. It should be noted that regions with correlation coefficients less than 0.4 are mainly observed in the central part of China. This suggests that changes in drought condition may be not a dominant factor for SM change, which could be explained by the influence of temperature and runoff (Zhao et al. 2021). Increased temperature leads to a higher evaporative demand and thus to a potential increase in evapotranspiration, possibly leading to a further decrease in SM (Seneviratne et al., 2010). Previous research revealed that the "runoff effect" reduces SM persistence substantially in parts of China and enhances in wet regions (Koster and Suarez 2001).

As the strong regionality of droughts (Zhang et al. 2020), this study further analyzed the changes in SM and SPEI-01 in summer for different regions over China. Figure 4 displays the time series of SPEI-01 and SM anomalies in four regions and throughout China. There are significant increasing trends of time series of SM anomaly in the four regions, indicating that SM has shown the characteristics of wetting over China in the past 40 years. Correlation coefficients between SM and SPEI-01 are 0.34 for arid, 0.64 for semiarid, 0.30 for semi-humid, and 0.48 for humid. Time series of SM and SPEI-01 generally show consistence in terms of both long-term trend and inter-annual variations, suggesting that SPEI-01 can virtually precisely capture the change of SM over the study period.

Additionally, we referred to the *Analysis of Major Drought Events in China (1961–2020)* by Zou et al. (2021) to further analyze the corresponding relationship between the two through typical historical drought events in different regions. For instance, the drought event in 1985 in Xinjiang; the severe drought events in 2001 in Xinjiang, Qinghai, and Gansu; and the extreme drought events in 2009 in Gansu all show negative anomalies of SM and SPEI in arid regions
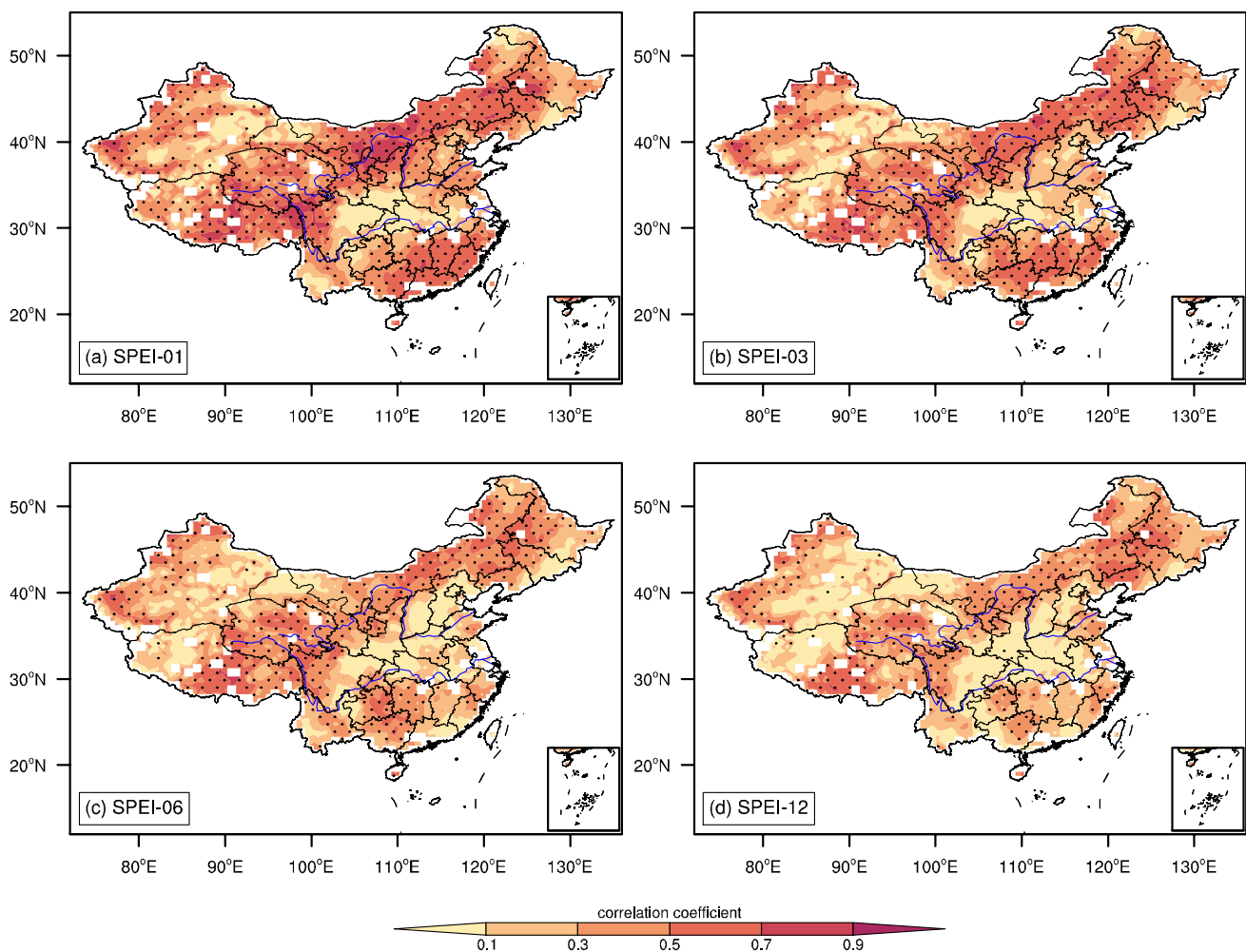
**Fig. 3** The correlation coefficients between SM and SPEI-01 (**a**), SPEI-03 (**b**), SPEI-06 (**c**), and SPEI-12 (**d**) for the period of 1979–2019 in China. The solid dots indicate trends significant at 95% confidence level

(Fig. 4a), and their intensity is also displayed (Fig. 4a). For the same reason, two severe drought events happening in Inner Mongolia in 2010 and 2015 in semiarid regions, two extreme drought events (1982 and 2015) occurring in semi-humid regions, and drought occurrence in 2003 and 2011 in most parts of humid regions can be shown in Fig. 4 b–d. Through the above correlation analysis between SPEI at different time scales and SM, as well as the reflection of soil moisture changes and extreme drought events in different regions, we conclude that SPEI-01 has a good applicability in drought identification for different regions of China and is therefore used in the following analysis regarding drought severity assessment.

### 3.3 Spatial pattern of the change in summer drought over China

On the basis of above results, we explored the changes in summer drought using SPEI-01. Figure 5a depicts the

summer SPEI-01 trend during 1961–2020. There is a significant drying trend in the east of Xinjiang, the Beijing-Tianjin-Hebei region, most parts of Inner Mongolia, and southwest of China in summer. By contrast, drought relief was mainly observed in the west of Xinjiang, most parts of Tibetan Plateau, and Yangtze River Delta.

Spatial pattern regarding summer drought change was also derived using other drought indices based on in situ observation. To verify the spatial similarity of trends, the grid data was interpolated to the stations based on nearest neighbor interpolation, and the trend consistency is analyzed. The consistency ratio between the grid SPEI and four drought indices based on observation is 59%, 71%, 56%, and 64%. The density scatterplot (Fig. 5 b–e) shows that the grid SPEI and the four drought indices based on the observation reveal a good consistency, with correlation coefficients of 0.58, 0.71, 0.56, and 0.52 ($p < 0.01$), respectively, and the RMSE less than 1. Therefore, although there exist some differences in values of trends and significance, four drought
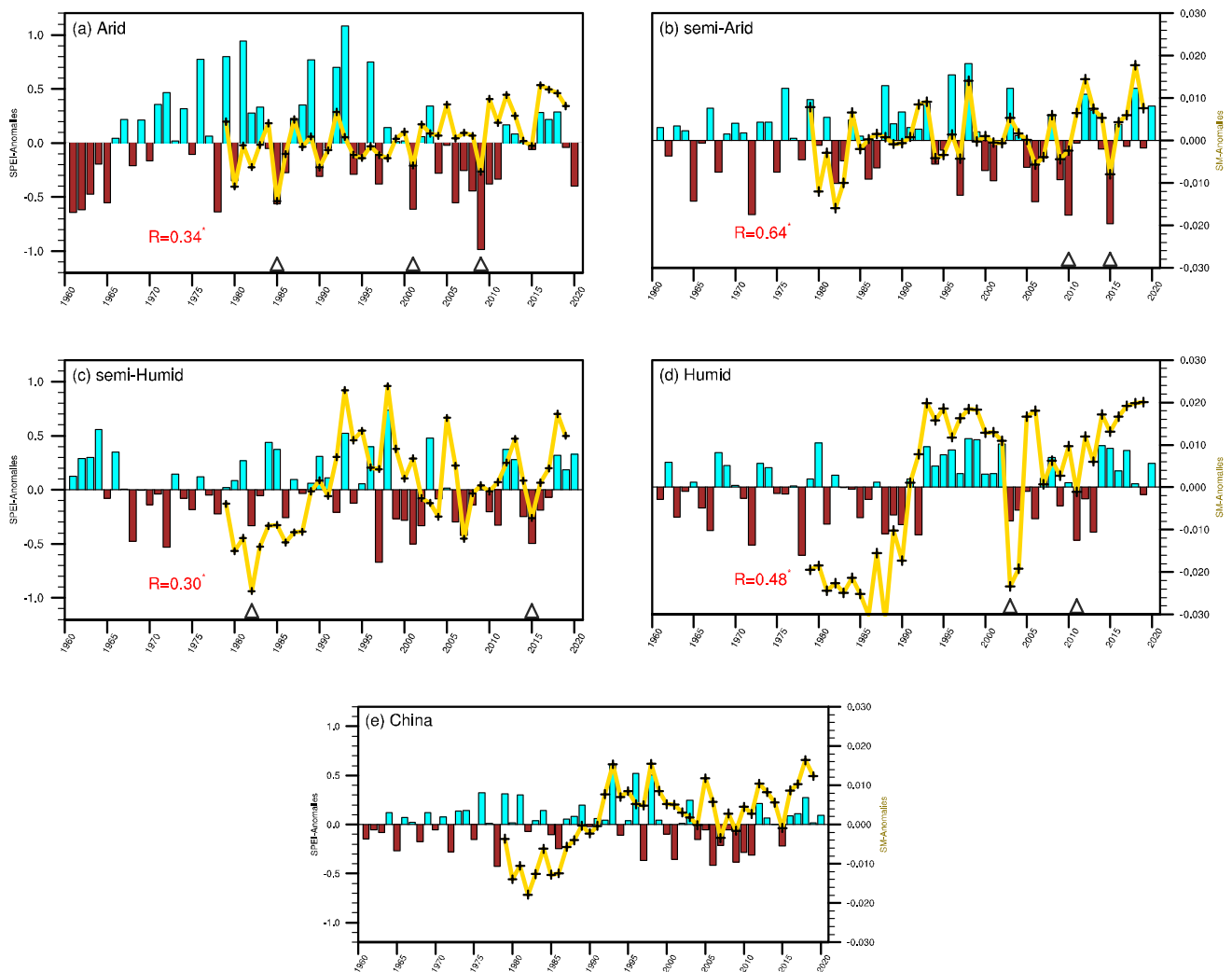
**Fig. 4** Time series of anomaly of SPEI-01 (bars) and SM (marker lines) in dry (**a**), semi-dry (**b**), semi-humid (**c**), humid (**d**) regions, and China (**e**) in summer during 1961–2020. The black triangle rep- resents drought events recorded. The red numbers with stars denote significant correlation coefficients between SM and SPEI ($p < 0.05$)

indices overall show similar spatial distributions regarding drought condition change to the grid SPEI-01. The values of different indices show an increasing trend (drought relief) in northwest region and the eastern China and a decreasing trend (drought exacerbation) in southwest and north China.

### 3.4 Change in the frequency of summer drought across regions

In order to analyze the changes in drought frequency, we calculated the trend of drought frequency in summer in different regions during 1961–2020 based on the drought classification of SPEI-01. As Table 3 illustrated, in the arid and semiarid regions, mild drought shows a decreasing trend (both −0.02/10a), while an increasing trend in moderate drought (0.21/10a and 0.01/10a, *p < 0.05*). For semi-humid

regions, there is almost no obvious trend change between mild and moderate drought (0.002/10a and −0.004/10a). The frequency of severe drought and extreme drought has no trend in these three regions. In humid regions, the trends of drought frequency are all zero per decade during 1961–2020. The results indicate a slight trend of transition from mild to moderate drought in arid and semiarid regions. However, in semi-humid and humid regions, there is no obvious trend of change in the frequency of drought in summer from 1961 to 2020. Wang et al. (2015) used SPEI and SPI to analyze drought changes in China over the past 50 years, showing that there is no evidence of the increase in drought severity over China taking the whole country into account. Therefore, this also explains laterally that there is no significant change trend in drought frequency of different intensities in the four regions.
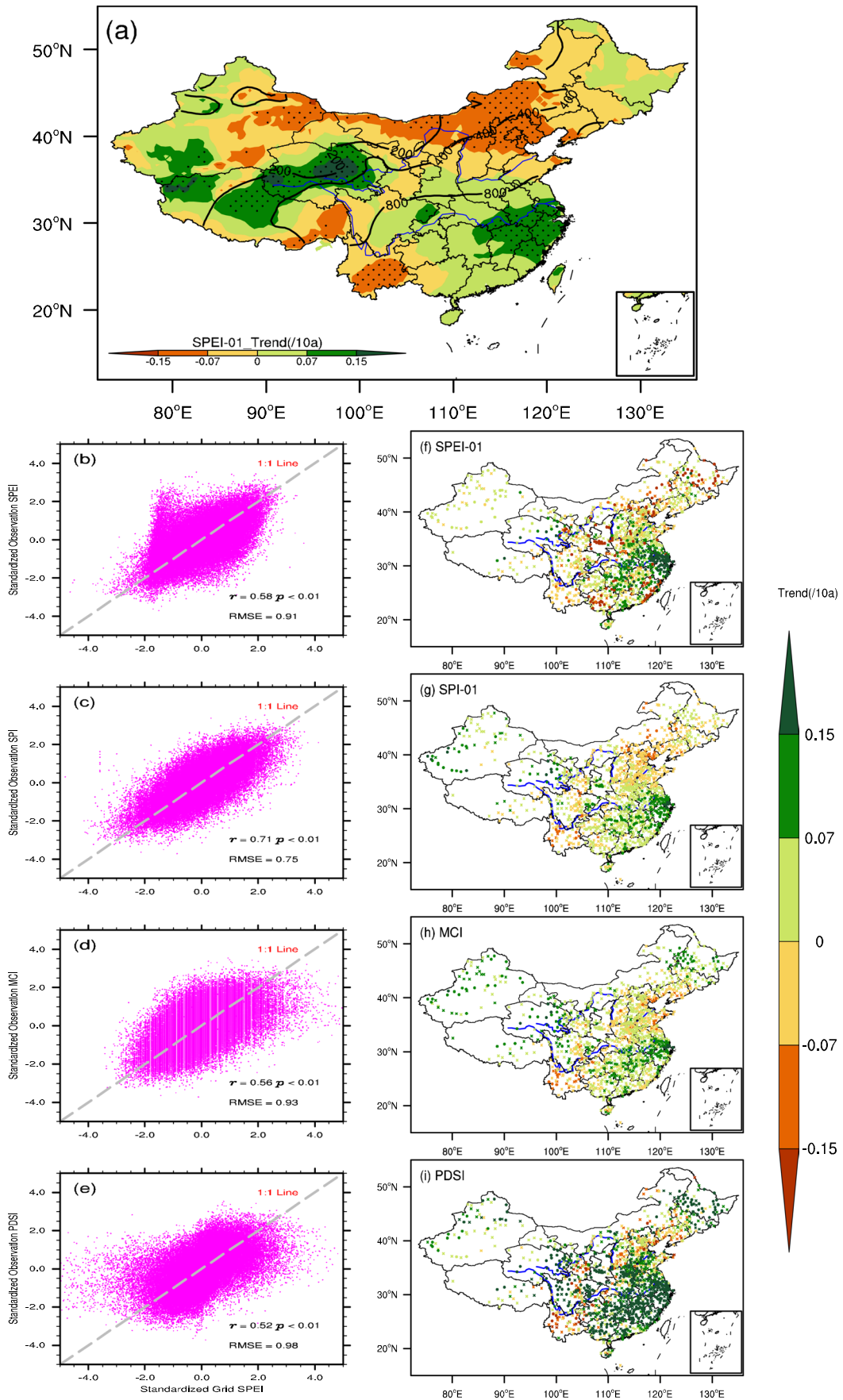
Figure 6 a and c shows the spatial distribution of accumulating frequency of drought above mild drought and severe drought. Summer droughts are mainly concentrated in western China, especially in the northwest of Inner Mongolia, Tarim Basin, southwest China, and western Tibet (Fig. 6a). The occurrence frequency of drought events above severe drought is less than 3 in the past 60 years, but it still shows regional characteristics (Fig. 6c). The high value areas are mainly located in the central and western Inner Mongolia, the northern and southern parts of the Xinjiang, and the west of the Tibetan Plateau, indicating that it is more prone to extreme drought events in these regions. It is also noticeable that although Tibetan Plateau is warming and wetting, due to its ecological vulnerability and sensitivity to climate (Shen et al. 2011), the occurrence of extreme drought events still worths more deeper analyses.

Considering there is no obvious trend of occurrence frequency with different intensities in different regions (Table 3), this study analyzed the changes in drought frequency per decade, as shown in Fig. 6 b and d. Bars with different colors represent the average accumulating frequency, and the maximum is displayed by short horizontal lines. For semi-humid and humid regions (green and gold bars), the occurrence frequency of every decade is maintained at a relatively stable level with little fluctuation. For arid and semiarid areas (red and blue bars), it is obvious that in the first decade of the twenty-first century, the frequency of severe drought events has increased sharply (the average value is much higher than those in other decades). And in Fig. 4 a–b, it can also be shown that the most negative SPEI-01 anomalies occurred in 2000–2010. In the first four decades, the frequency of events above severe drought in arid regions has a significantly increasing trend. It has turned in the first decade of the twenty-first century, although the frequency of severe drought events has decreased in the last decade; it can still be found that events above severe drought have a strong fluctuation every decade in arid regions. Semiarid regions also show similar characteristics.

### 3.5 Change in the intensity of summer drought across regions

As shown in Fig. 7, the proportion of mild drought is the highest, accounting for more than 50% per decade in four regions, indicating that mild drought is a major drought type in China. The proportion of moderate drought is about 20%,

that of severe drought is less than 10%, and extreme drought is less than 5%. And extreme drought events are mainly occurring in arid and semiarid areas (Fig. 7 a–b). For arid and semiarid areas, we found that in the first 10 years of the twenty-first century, drought events occurred frequently, and intensity increased, showing the transformation from mild to drought of other intensity (the proportion of light drought decreases, and the proportion of moderate and severe drought increases obviously). In arid areas, compared to the decade before 2000 (i.e., 1990–2000), the proportion of mild drought decreased by nearly 11% (from 78 to 67%) between 2010 and 2020, while other types of droughts increased to varying degrees. And in semiarid areas, the proportion is mainly represented by a decrease in severe drought (from 7 to 5%) and an increase in the proportion of moderate (from 23.5 to 24.6%) and extreme drought (from 0.1 to 2.6%). It is worth noting that in semiarid regions, the proportion of mild drought has rebounded during 2010–2020; the proportion of extreme drought has also increased significantly. For semi-humid regions, the proportion of drought events with different intensity has no conspicuous change (Fig. 7c). For humid regions, after the 1980s, the intensity of drought increased slightly, showing a rise in the proportion of severe drought (from 2.5 to 3.5%). The results indicate the following: (a) the intensity of drought has become polarized in arid and semi-arid regions in the past 20 years, which brings challenges to drought monitoring and early warning, and (b) for humid regions, the intensity of drought events has increased in the past three decades, and more attention should be paid to the impact of drought events in humid regions in the future.

## 4 Conclusion and discussions

This study utilized grid SPEI to analyze the changes in summer drought conditions (change in trend, intensity, and frequency of drought) in arid, semiarid, semi-humid, and humid regions over China from 1961 to 2020. Satellite retrieval SM is used as an indicator to find the SPEI with the applicable time scale. Our results confirmed that SPEI-01 has good performance in reflecting summer SM and drought changes during 1961–2020. Using SPEI-01, we also revealed the spatiotemporal characteristics of drought

**Table 3** Trends of frequency of different intensities of drought in four regions (/10a)

|  | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| Arid | −0.020 | 0.21 | 0 | 0 |
| Semi-arid | −0.020 | 0.01 | 0 | 0 |
| Semi-humid | 0.002 | −0.004 | 0 | 0 |
| Humid | 0 | 0 | 0 | 0 |
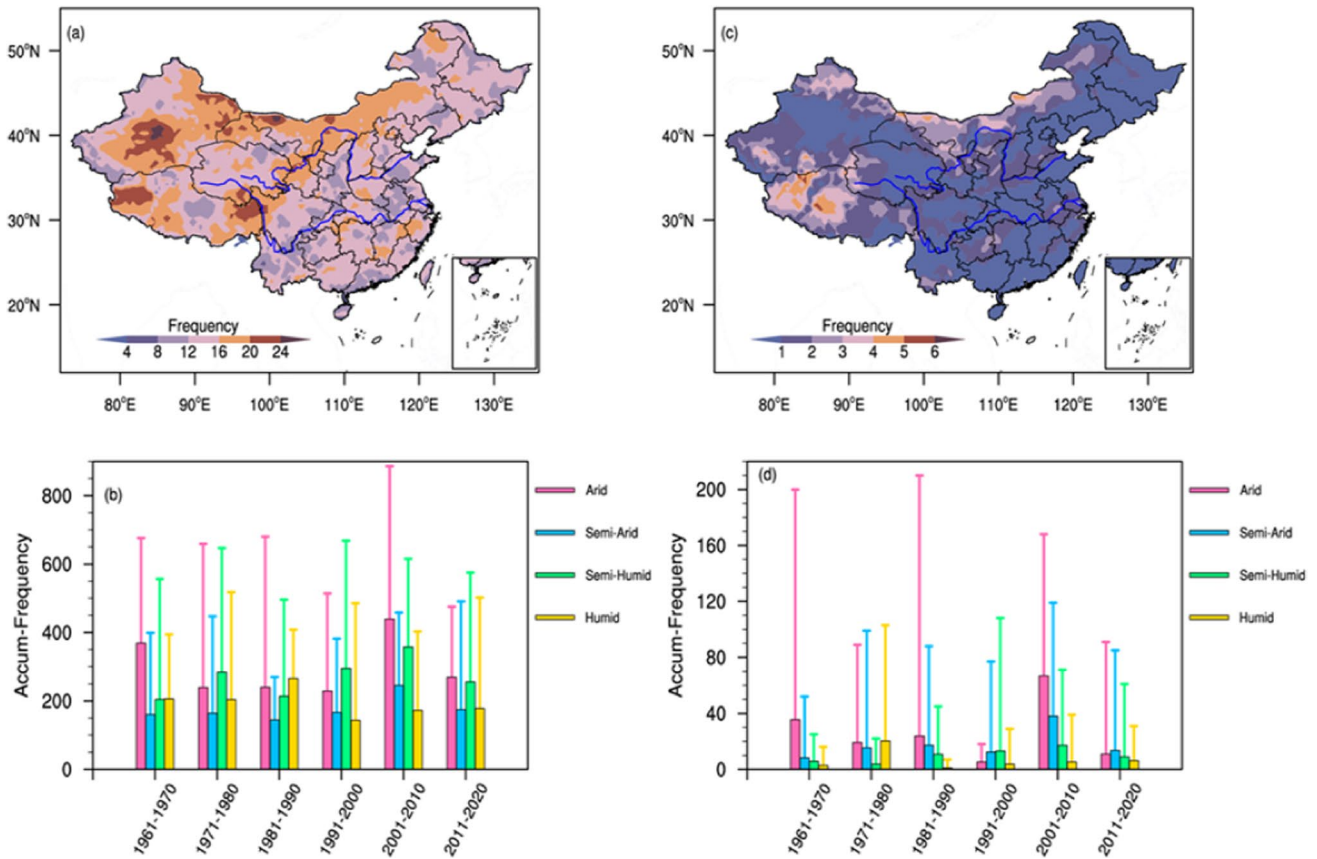
**Fig. 6** The spatial distribution of accumulating occurrence frequency of drought events above mild (**a**) and severe (**c**) drought during 1961–2020. The accumulating occurrence frequency above mild (**b**) and severe (**d**) drought every decade in different regions

frequency and intensity in different climate regions of China, showing that since the twenty-first century, in arid, semiarid, and humid regions, the frequency of drought has increased, the intensity of drought tends to polarization, and more serious drought events occur frequently.

This study provides a scientific understanding of summer drought changes in China during the past 60 years. Throughput analysis, we also noticed that inconsistent changes in

the trends of precipitation and SM exist, and the correlation coefficients between SPEI and SM are low, mainly in Central China, which may be related to human activities such as irrigation and land use (Huang et al. 2020; Chiang et al. 2021). IPCC AR6 WGI provides the latest assessment conclusions, suggesting that the attribution of drought trend changes is not reliable at present (Seneviratne et al. 2021). Thus, attribution studies in China will need to be strengthened. Future
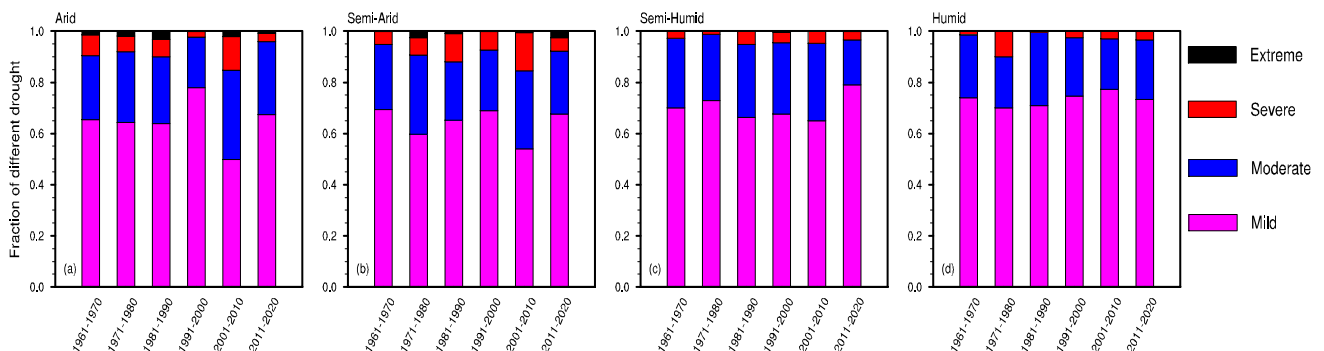


**Fig. 7** The proportion of accumulating occurrence frequency of drought events with different drought intensity in arid (**a**), semiarid (**b**), semi-humid (**c**), and humid regions (**d**)

work will focus on clarifying the reasons for the inconsistency and conducting attribution studies on drought changes.

Our research provides reliable conclusions about the changes in the frequency and intensity of summer drought events in China. This study pointed out that after entering the twenty-first century, seasonal drought events increased significantly (Chen and Sun 2015; Zhang et al. 2020). At the same time, with the continuous intensification of climate change, flash drought (a rapidly intensifying drought) and drought-related compound events on a short-time scale occur frequently in China (Wang and Yuan, 2018; Yu and Zhai 2020). Besides, the impact of droughts could exist until several years after the event ends (Saatchi et al. 2013; Schwalm et al. 2017; Anderegg et al. 2020). For example, previous studies found that the forests exhibit a drought "legacy effect," with 3 to 4 years' decreasing growth of forests (Anderegg et al. 2015). Moreover, the capacity of forests as carbon sinks will be weakened (Anderegg et al. 2015). Recent research used ring-width index to investigate the impact and legacy effects of extreme drought events (Huang et al. 2018). The results not only revealed that extreme droughts during the dry season have more serious impact than wet season but also emphasized the importance of timing of drought. Thus, future work is needed to explore the changes and impacts of drought events in other seasons (mainly spring and autumn) and at interannual and different seasonal scales combined with reanalysis data.

In addition, AR6 focuses on assessing the change of atmospheric evaporation demand (AED). IPCC AR6 WGI Report further points out that AED will increase under different scenarios with climate warming (Seneviratne et al. 2021). In the future, AED has garnered considerable interest in the future as a key driver of different types of droughts (Wang et al. 2022). The change of AED is a response to climate change, as the driving factor of different types of drought change. Therefore, in addition to considering precipitation, temperature, and SM, AED is further introduced to analyze the dominant factor affecting changes in drought in different regions.

## Declarations

## References

An R, Zhang L, Wang Z et al (2016) Validation of the ESA CCI soil moisture product in China. Int J Appl Earth Obs Geoinf 48:28–36. https://doi.org/10.1016/j.jag.2015.09.009

Anderegg WRL, Schwalm C, Biondi F et al (2015) Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. Science 349(6247):528–532

Anderegg WRL, Trugman AT, Badgley G, Konings AG, Shaw J (2020) Divergent forest sensitivity to repeated extreme droughts. Nat Clim Chang 10(12):1091–1095

Beguería S, Vicente S, Sergio M et al (2022) SPEIbase v.2.7 [Dataset]. DIGITAL.CSIC. Version 2.7. https://doi.org/10.20350/digitalCSIC/14612

Begueria S, Vicente-Serrano SM, Angulo-Martinez M (2010) A multiscalar global drought dataset: the SPEI base: a new gridded product for the analysis of drought variability and impacts. Bull Am Meteorol Soc 91:1351–1354

Beguería S, Vicente-Serrano SM, Reig F et al (2014) Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. Int J Climatol 34(10):3001–3023

Beguería S, Vicente-Serrano SM, Tomás-Burguera M, Maneta M (2016) Bias in the variance of gridded data sets leads to misleading conclusions about changes in climate variability. Int J Climatol 36(9):3413–3422. https://doi.org/10.1002/joc.4561

Busch FA, Niemann JD, Coleman M (2012) Evaluation of an EOF-based method to downscale soil moisture patterns based on topographical attributes. Hydrol Process 26(18):2696–2709. https://doi.org/10.1002/hyp.8363

Cao S, Zhang L, He Y et al (2022) Effects and contributions of meteorological drought on agricultural drought under different climatic zones and vegetation types in northwest China. Sci Total Environ 821:153270

Chen H, Sun J (2015) Changes in drought characteristics over China using the standardized precipitation evapotranspiration index. J Clim 28(13):150414125419009

Chiang F, Mazdiyasni O, AghaKouchak A (2021) Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. Nat Commun 12:2754. https://doi.org/10.1038/s41467-021-22314-w

Crow WT, Ryu D (2009) A new data assimilation approach for improving runoff prediction using remotely-sensed soil moisture

retrievals. Hydrol Earth Syst Sci 13:1–16. https://doi.org/10.5194/hess-13-1-2009

Dai A, Zhao T (2017) Uncertainties in historical changes and future projections of drought. Part I: estimates of historical drought changes. Clim Chang 144(3):519–533. https://doi.org/10.1007/s10584-016-1705-2

Dorigo W, Wagner W, Albergel C et al (2017) ESA CCI soil moisture for improved Earth system understanding: state-of-the art and future directions. Remote Sens Environ 203:185–215. https://doi.org/10.1016/j.rse.2017.07.001

Hayes MJ (2006) Drought indices. American Cancer Society

Hollmann R, Merchant CJ, Saunders R et al (2013) The ESA Climate Change Initiative: satellite data records for essential climate variables. Bull Am Meteorol Soc 94(10):1541–1552. https://doi.org/10.1175/BAMS-D-11-00254.1

Huang M, Wang X, Keenan TF et al (2018) Drought timing influences the legacy of tree growth recovery. Glob Chang Biol 24(8):3546–3559

IPCC (2013) Climate Change 2013: the physical science basis. Cambridge University Press, Cambridge

IPCC (2021) Climate Change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press

Keyantash J, Dracup JA (2002) The quantification of drought: an evaluation of drought indices. Bull Am Meteorol Soc 83(8):1167–1180. https://doi.org/10.1175/1520-0477-83.8.1167

Khong A, Wang JK, Quiring SM, Ford TW (2015) Soil moisture variability in Iowa. Int J Climatol 35:2837–2848. https://doi.org/10.1002/joc.4176

Koster RD, Suarez MJ (2001) Soil moisture memory in climate models. J Hydrometeorol 2(6):558–570

Labudová L, Labuda M, Takáč J (2017) Comparison of SPI and SPEI applicability for drought impact assessment on crop production in the Danubian Lowland and the East Slovakian Lowland. Theor Appl Climatol 128:491–506

Li M, Ma Z (2012) Soil moisture-based study of the variability of dry-wet climate and climate zone in China. Chin Sci Bull 58:531–544

Li X, Li Y, Chen A et al (2019) The impact of the 2009/2010 drought on vegetation growth and terrestrial carbon balance in southwest China. Agric For Meteorol 269:239–248

Li Z, Zhou T, Zhao X et al (2015) Assessments of drought impacts on vegetation in China with the optimal time scales of the climatic drought index. Int J Environ Res Public Health 12:7615–7634

Liao Y, Zhang C (2017) Spatio-temporal distribution characteristics and disaster change of drought in China based on meteorological drought composite index. Meteorol Mon 43(11):1402–1409 (in Chinese). https://doi.org/10.7519/j.issn.1000-0526.2017.11.009

Ling X, Huang Y, Guo W et al (2021) Comprehensive evaluation of satellite-based and reanalysis soil moisture products using in situ observations over China. Hydrol Earth Syst Sci 25(7):4209–4229

Ma S, Zhu K, Li M et al (2016) Comparative study on multi-source soil moisture data in China. Clim Environ Res 21(2):121–133 (in Chinese). https://doi.org/10.3878/j.issn.1006-9585.2015.15080

McKee TB (1995) Drought monitoring with multiple time scales. Proceedings of 9th Conference on Applied Climatology, Boston. https://doi.org/10.1109/INFCOM.1996.493342

Huang MT, Zhou BQ, Zhai PM (2020) Impacts of extreme weather and climate events on desertification, land degradation and food security. Adv Clim Chang Res 16(1):17–27 (in Chinese)

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391(1-2):202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Mukherjee S, Mishra A, Trenberth KE (2018) Climate change and drought: a perspective on drought indices. Curr Clim Change Rep 4:145–163. https://doi.org/10.1007/s40641-018-0098-x

Palmer WC (1965) Meteorological drought. US Department of Commerce, Weather Bureau, Washington, DC

Peng J, Loew A (2017) Recent advances in soil moisture estimation from remote sensing. Water 9(7):530

Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc R Soc A 193:454–465

Pokhrel Y, Felfelani F, Satoh Y et al (2021) Global terrestrial water storage and drought severity under climate change. Nat Clim Chang 11:226–233. https://doi.org/10.1038/s41558-020-00972-w

Potop V, Možný M, Soukup J (2012) Drought at various time scales in the lowland regions and their impact on vegetable crops in the Czech Republic. Agric Forest Meteorol 156:121–133

Potopová V, Štěpánek P, Možný M et al (2015) Performance of the standardized precipitation evapotranspiration index at various lags for agricultural drought risk assessment in the Czech Republic. Agric For Meteorol 202:26–38

Saatchi S et al (2013) Persistent effects of a severe drought on Amazonian forest canopy. Proc Natl Acad Sci 110(2):565–570

Schwalm C, Anderegg W, Michalak A et al (2017) Global patterns of drought recovery. Nature 548:202–205. https://doi.org/10.1038/nature23021

Seneviratne SI, Zhang X, Adnan M et al (2021) Weather and climate extreme events in a changing climate. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press

Seneviratne SI et al (2010) Investigating soil moisture–climate interactions in a changing climate: a review. Earth Sci Rev 99(3–4):125–161. https://doi.org/10.1016/j.earscirev.2010.02.004

Shen MG, Tang YH, Chen J et al (2011) Influences of temperature and precipitation before the growing season on spring phenology in grasslands of the central and eastern Qinghai-Tibetan Plateau. Agric For Meteorol 151(12):1711–1722. https://doi.org/10.1016/j.agrformet.2011.07.003

Sims AP, Niyogi DS, Raman S (2002) Adopting drought indices for estimating soil moisture: a North Carolina case study. Geophys Res Lett 29(8):24–21. https://doi.org/10.1029/2001GL013343

Song D, Zhao K, Guan Z (2007) Advances in research on soil moisture by microwave remote sensing in China. Chin Geogr Sci 17:186–191. https://doi.org/10.1007/s11769-007-0186-7

Spinoni J, Barbosa P, Bucchignani E et al (2020) Future global meteorological drought hot spots: a study based on CORDEX data. J Clim 33(9):3635–3661. https://doi.org/10.1175/JCLI-D-19-0084.1

Su B, Huang J, Fischer T et al (2018) Drought losses in China might double between the 1.5 °C and 2.0 °C warming. Proc Natl Acad Sci U S A 115(42):10600–10605. https://doi.org/10.1073/pnas.1802109115

Trenberth KE, Dai A, vans der Schrier G, Jones PD, Barichivich J, Briffa KR et al (2014) Global warming and changes in drought. Nat Clim Chang 4:17. https://doi.org/10.1038/nclimate2067

Vicente-Serrano SM, Beguería S, López-Moreno JI et al (2010a) A global 0.5° gridded dataset (1901-2006) of a multiscalar drought index considering the joint effects of precipitation and temperature. J Hydrometeorol 11(4):1033–1043. https://doi.org/10.1175/2010JHM1224.1 http://digital.csic.es/handle/10261/23906

Vicente-Serrano SM, Beguería S, Lorenzo-Lacruz J et al (2012) Performance of drought indices for ecological, agricultural, and hydrological applications. Earth Interact 16:1–27. https://doi.org/10.1175/2012EI000434.1

Vicente-Serrano SM, Beguería S, Santiago L-M, Juan I (2010b) A multiscalar drought index sensitive to global warming: the

standardized precipitation evapotranspiration index. J Clim 23(7):1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Vicente-Serrano SM, Gouveia C, Camarero JJ et al (2013) Response of vegetation to drought time-scales across global land biomes. Proc Natl Acad Sci 110(1):52–57

Vogt J, Erian W, Pulwarty R et al (2021) GAR Special Report on Drought 2021. United Nations

Wang A, Bohn TJ, Mahanama SP et al (2009) Multimodel ensemble reconstruction of drought over the continental United States. J Clim 22(10):2694. https://doi.org/10.1175/2008JCLI2586.1

Wang A, Lettenmaier DP, Sheffield J (2011) Soil moisture drought in China, 1950–2006. J Clim 24(13):3257–3271. https://doi.org/10.1175/2011JCLI3733.1

Wang CP, Huang MT, Zhai PM (2022) New progress and enlightenment on different types of drought changes from IPCC Sixth Assessment Report. Acta Meteor Sin 80(1):168–175 (in Chinese)

Wang L, Yuan X (2018) Two types of flash drought and their connections with seasonal drought. Adv Atmos Sci 35(12):1478–1490

Wang W, Zhu Y, Xu R et al (2015) Drought severity change in China during 1961–2012 indicated by SPI and SPEI. Nat Hazards 75:2437–2451

Wang Z, Zhai P (2003) Climate change in drought over northern China during 1950-2000. Acta Geograph Sin 58(7):61–68 (in Chinese). https://doi.org/10.11821/xb20037s007

Wilhite DA (2000) Chapter 1 Drought as a natural hazard: concepts and definitions. Drought Mitigation Center Faculty Publications, p 69

Wu M, Li Y, Hu W et al (2020) Spatiotemporal variability of standardized precipitation evapotranspiration index in mainland China over 1961-2016. Int J Climatol 40(23):4781–4799. https://doi.org/10.1002/joc.6489

Xu H, Wang X, Zhao C et al (2021) Seasonal and aridity influences on the relationships between drought indices and hydrological variables over China. Weather Clim Extrem 34:100393

Yang Q, Li MX, Zheng ZY et al (2017) Regional applicability of seven meteorological drought indices in China. Sci China Earth Sci 60:745–760

Yao J, Zhao Y, Chen Y et al (2018a) Multi-scale assessments of droughts: a case study in Xinjiang, China. Sci Total Environ 630:444–452

Yao N, Li Y, Lei T et al (2018b) Drought evolution, severity and trends in mainland China over 1961–2013. Sci Total Environ 616:73–89

Yu R, Zhai PM (2020) More frequent and widespread persistent compound drought and heat event observed in China. Sci Rep 10(1):1–7. https://doi.org/10.1038/s41598-020-71312-3

Zhai J, Su B, Krysanova V et al (2010) Spatial variation and trends in PDSI and SPI indices and their relation to streamflow in 10 large regions of China. J Clim 23(3):649–663

Zhai PM, Zhang XB, Wan H et al (2005) Trends in total precipitation and frequency of daily precipitation extremes over China. J Clim 18(7):1096–1108

Zhang Q, Han LY, Hao XC et al (2015) On the impact of the climate change on the agricultural disaster loss caused by drought in China and the regional differences between the North and the South. Acta Meteor Sin 73(6):1092–1103 (in Chinese)

Zhang Q, Yao Y, Li Y et al (2020) Progress and prospect on the study of causes and variation regularity of droughts in China. Acta Meteor Sin 78(3):500–521 (in Chinese). https://doi.org/10.11676/qxxb2020.032

Zhang Q, Yao YB, Wang Y et al (2019) Characteristics of drought in southern China under climatic warming, the risk, and countermeasures for prevention and control. Theor Appl Climatol 136:1157–1173. https://doi.org/10.1007/s00704-018-2541-2

Zhao J, Wang A, Wang H (2021) Soil moisture memory and its relationship with precipitation characteristics in China region. Chin J Atmos Sci 45(4):799–818 (in Chinese)

Zou XK, Zhai PM, Zhang Q (2005) Variations in droughts over China: 1951–2003. Geophys Res Lett 32(4):353–368. https://doi.org/10.1029/2004GL021853

Zou XK et al (2021) Analysis of major drought events in China (1961-2020). Science Press, Beijing