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Notes and Correspondence
Understanding and detecting super-extreme droughts in Southwest China through an integrated approach and index

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In the last decade, a series of super-extreme droughts have swept across Southwest China (SWC). However, the essential features behind them are not yet fully understood and traditional drought indices as well as precipitation fail to describe them, due to the lack of a comprehensive treatment of drought. We propose an integrated metric, the Comprehensive Multiscalar Indicator (CMI), as a new criterion for super-drought detection. Re-examination of SWC droughts illuminates the essential feature of super-drought events: a combination of multiple stresses on water resources, which highlights the utility of the CMI.

Key Words: super-extreme drought; multiscalar nature; integrated approach; Comprehensive Multiscalar Indicator

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1. Introduction

In recent decades, Southwest China (SWC) has experienced three super-extreme droughts – one in the summer of 2006, one from the autumn of 2009 to the spring of 2010, and one in the summer of 2011 – which have resulted in tremendous economic loss, ecosystem damage, and disruption of society (Qiu, 2010; Wang *et al.*, 2015; Ye *et al.*, 2012; Zhang *et al.*, 2012a, 2012b, 2015). According to Chinese government statistics, the severe drought during summer 2006 caused water scarcity for at least 18 million residents, crop failure on 311 300 ha, and economic losses of 11.74 billion yuan (official currency in China) (Li *et al.*, 2009). During the long-lasting drought from the autumn of 2009 to the ensuing spring of 2010, more than 16 million people and 11 million livestock faced drinking-water shortages, with direct economic losses estimated at 19 billion yuan (Barriopedro *et al.*, 2012; Yang *et al.*, 2012; Zhang *et al.*, 2013). One year later, drought struck SWC again, causing water shortages for 9.17 million livestock and 12 million people as well as destroying 5.86 million ha of crops (Sun *et al.*, 2012; Wang *et al.*, 2012). Due to their far-reaching and devastating impacts, the most calamitous droughts in SWC received national attention from both the Chinese government and the academic sector.

The SWC droughts have become the subject of extensive studies, which are attempting to illuminate their historical changes and atmospheric and oceanic causes. Many past efforts placed the current SWC precipitation anomalies in a historical perspective and concluded that the recent drought is the most severe in the last 50 years. For example, Li *et al.* (2009) found that in 2006 the summer rainfall in SWC reached its lowest level since 1959, suggesting that the 2006 summer drought was the most severe of any from 1959 to 2006. Based on precipitation anomalies, Yang *et al.* (2012) and Barriopedro *et al.* (2012) both reported that the winter drought during 2009/2010 was the strongest in the past half-century. Zhang *et al.* (2013) compared the autumn precipitation in SWC with the climatology and pointed out that the most severe autumn drought was recorded in 2009. In the recent work by Feng *et al.* (2014), however, rainfall shortages from winter to spring were even more severe in some previous years (1966, 1984 and 1986) than in 2010, which is a substantial contradiction of previous results. Why is there so much disagreement among previous results? These studies have depended on precipitation to characterize super-extreme drought, but this is insufficient, as will be illuminated in section 4, because precipitation reflects just one component of water resources and reflects merely short-term drought. A similar weakness is also found for traditional drought indices as reviewed in section 3. In short, the failure of using precipitation as well as traditional drought indices to recognize super-extreme droughts originates from the absence of a comprehensive treatment of drought. In view of this problem, we re-examine the historical change in drought in SWC via an integrated approach, in order to explain why the recent super-droughts are historically unprecedented and to disclose the essential features behind them. Moreover, we

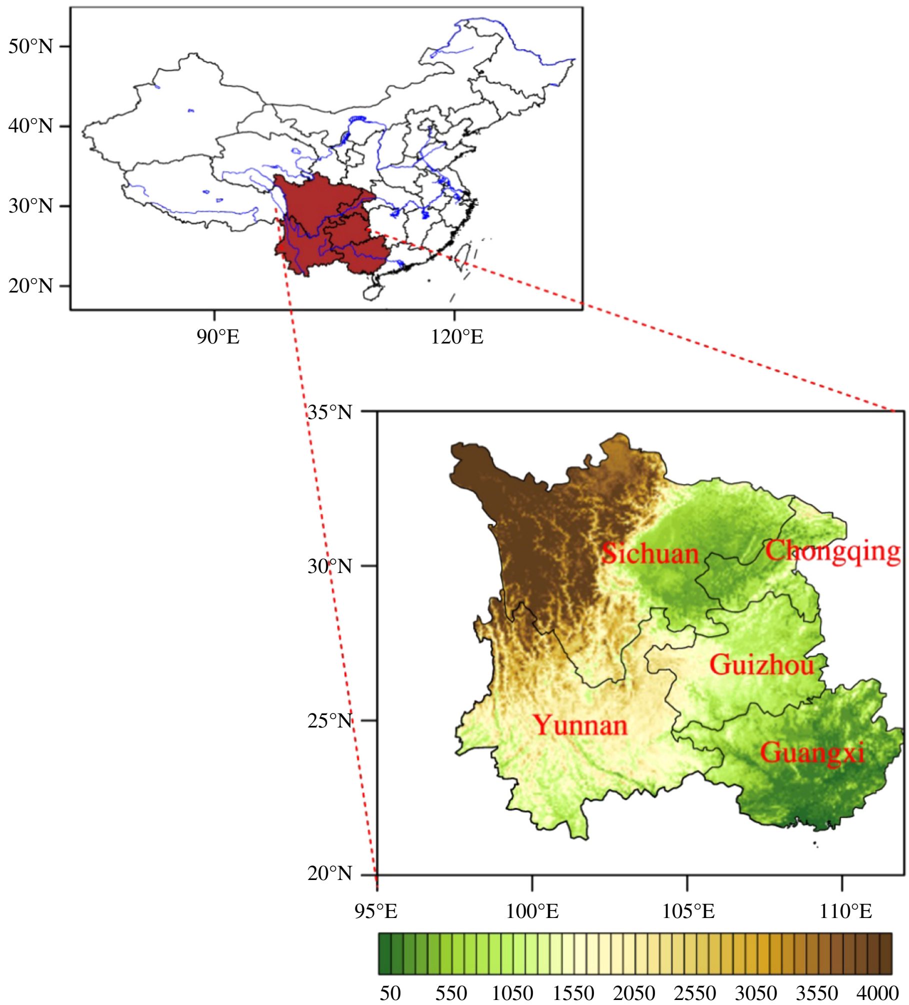

Figure 1. Location of Southwest China (top left) and its topography (bottom right, units: m).

develop an integrated index capable of detecting super-drought events and excluding inconsequential ones.

This article is structured as follows: the datasets employed in this study are briefly introduced in section 2; the fundamental principles of the integrated treatment of drought and a corresponding index called the Comprehensive Multiscalar Indicator (CMI) are described thoroughly in section 3; section 4 revisits the droughts in SWC through integrated water accounting along with CMI, in order to capture the essential features of the current super-droughts. Finally, conclusions and further discussion are given in section 5.

2. Datasets

Monthly precipitation and potential evapotranspiration (PET) on a 0.5° latitude–longitude grid, required for calculating the Standard Precipitation Evapotranspiration Index (SPEI), are retrieved from the National Meteorological Information Center of the China Meteorological Administration (NMIC/CMA) and the latest version (TS3.2) of the Climatic Research Unit (CRU)(Harris *et al.*, 2014), respectively. The precipitation dataset from NMIC/CMA is derived from gauge observations from 2474 stations. A quality-control procedure is imposed on rain-gauge observations, and the topographic effect is taken into account in the process of interpolation. The PET data provided by the CRU are estimated with the Penman–Monteith parametrization scheme (Allen *et al.*, 1994), which is considered more physically realistic and is recommended by the Food and Agriculture Organization (FAO), since it accounts for the collaborative effects of radiation, temperature, humidity and wind speed. Due to the sparse observations and poor quality of observational data before 1960, data for the period from 1961 to 2011 were extracted for the analyses in this study. In addition, the horizontal grid of the precipitation dataset from NMIC/CMA is identical with that of PET from the CRU, facilitating further study without introducing added uncertainties due to the interpolation scheme.

Southwest China covers an area of approximately 1.23 million km^2, or 12.9% of China, and is composed of five provinces: Chongqing, Sichuan, Guizhou, Yunnan, and the west of Guangxi, as illustrated in Figure 1.

3. Comprehensive Multiscalar Indicator

Before describing the physical principle and construction of CMI, it is important to provide a brief review of drought indices. A drought index, which synthesizes information about wet and dry conditions, is central to identifying and quantifying drought phenomena and is especially important for policymakers. In past decades, the most popular drought indices with extensive application in the meteorological community have been the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI). PDSI, initiated by Palmer (1965) and improved by Wells *et al.* (2004), is based on a two-stage bucket model of the soil, enabling the measurement of the cumulative departure of atmospheric moisture supply and demand at the surface. Despite its physical foundation and inclusion of evaporative demand, PDSI represents a fixed time-scale that typically varies between 9 and 18 months, with spatial differences among regions depending on local characteristics (Vicente-Serrano *et al.*, 2011). In contrast, SPI, developed by McKee *et al.* (1993, 1995), is capable of quantifying drought on different time-scales. It is commonly accepted that drought is a multiscalar phenomenon, as reported by McKee *et al.* (1995), Byun and Wilhite (1999) and Hayes *et al.* (1999), highlighting the utility of a multiscalar drought index in capturing drought impact on different usable water resources. However, SPI is not suitable for drought assessment in future climates, since it depends on precipitation alone and the role of atmospheric evaporative demand is not taken into account. More recently, Vicente-Serrano *et al.* (2010a, 2010b) proposed a new drought index, SPEI, which combines the multiscalar nature of SPI and the sensitivity of PDSI to changes in evaporative demand. In addition, numerous studies have pointed out that PDSI is highly correlated with SPEI/SPI at a time-scale of 12 months or so (Guttman, 1998; Vicente-Serrano *et al.*, 2012), so PDSI is more relevant for applications at intermediate time-scales and can be viewed as a special case of SPEI. Consequently, we will use SPEI to discuss the relevant issues and to construct CMI. The detailed procedure to calculate SPEI can be found in the work by Vicente-Serrano *et al.* (2010a). SPEI has four drought severity classes: mild, moderate, severe and extreme (Table 1). Figure 2 depicts the historical variation in SPEI at the time-scales of 3, 6, 12, 24 and 48 months for the period of 1961 through to 2011. The three catastrophic events in SWC are not exceptional and discernible in SPEI at any one time-scale. For example, from the perspective of the 48-month SPEI, SWC remains persistently in an extreme drought phase from late 2006 to mid-2009, when no calamitous droughts with high impacts occurred. This is also the case for SPEI at other time-scales.

Subsequently, we will introduce the physical basis and construction of CMI. The phases and frequencies of dry/wet oscillations at different time-scales all differ; at times they are opposite and at other times they coincide (Figure 2). Therefore, it is conceivable that a super-event appears when extreme phases of short- and long-term droughts coincide. On the other hand, if the severe/extreme droughts at different time-scales occur in isolation, the destructive effect of the droughts may not be as serious, which is further elucidated as follows: (i) Meteorological and soil moisture drought can come on suddenly and can be severe due to inadequate rainfall within 1 or 2 months, posing a great threat to plants and crops. However, reservoirs, rivers and lakes may still provide sufficient water to irrigate crops; in other words, there is no hydrological drought, which thus prevents agricultural drought and famine. (ii) Long-term low precipitation can lead to reduced streamflow, the drying up of reservoirs, and a drop in groundwater levels, but high precipitation events during a hydrological drought period may produce normal or even high levels of soil moisture and thus meet crop demands. In either case, even if the drought at one typical time-scale is extreme,

Table 1. Classification of drought and corresponding probability according to SPEI values (Edwards *et al.*, 1997).

SPEI values	Drought category		Probability (%)
2.0 and above	Extreme wet		2.3
1.5 to 1.99	Severe wet		4.4
0 to 1.49	Moderate wet		9.2
0 to 0.99	Mild wet	Near normal	34.1
0 to −0.99	Mild drought		34.1
−1 to −1.49	Moderate drought		9.2
−1.5 to −1.99	Severe drought		4.4
−2 and less	Extreme drought		2.3

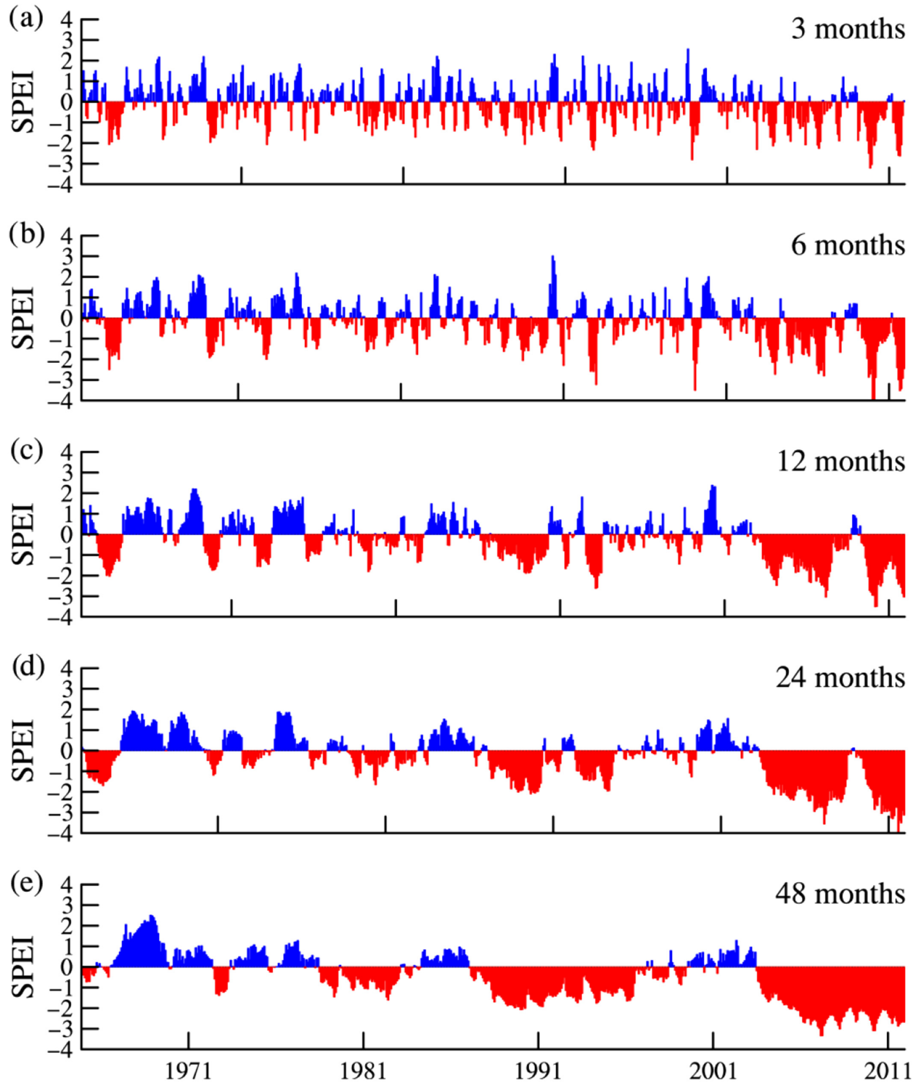

Figure 2. Time series of (a) 3-, (b) 6-, (c) 12-, (d) 24-, and (e) 48-month SPEI for Southwest China from 1961 to 2011.

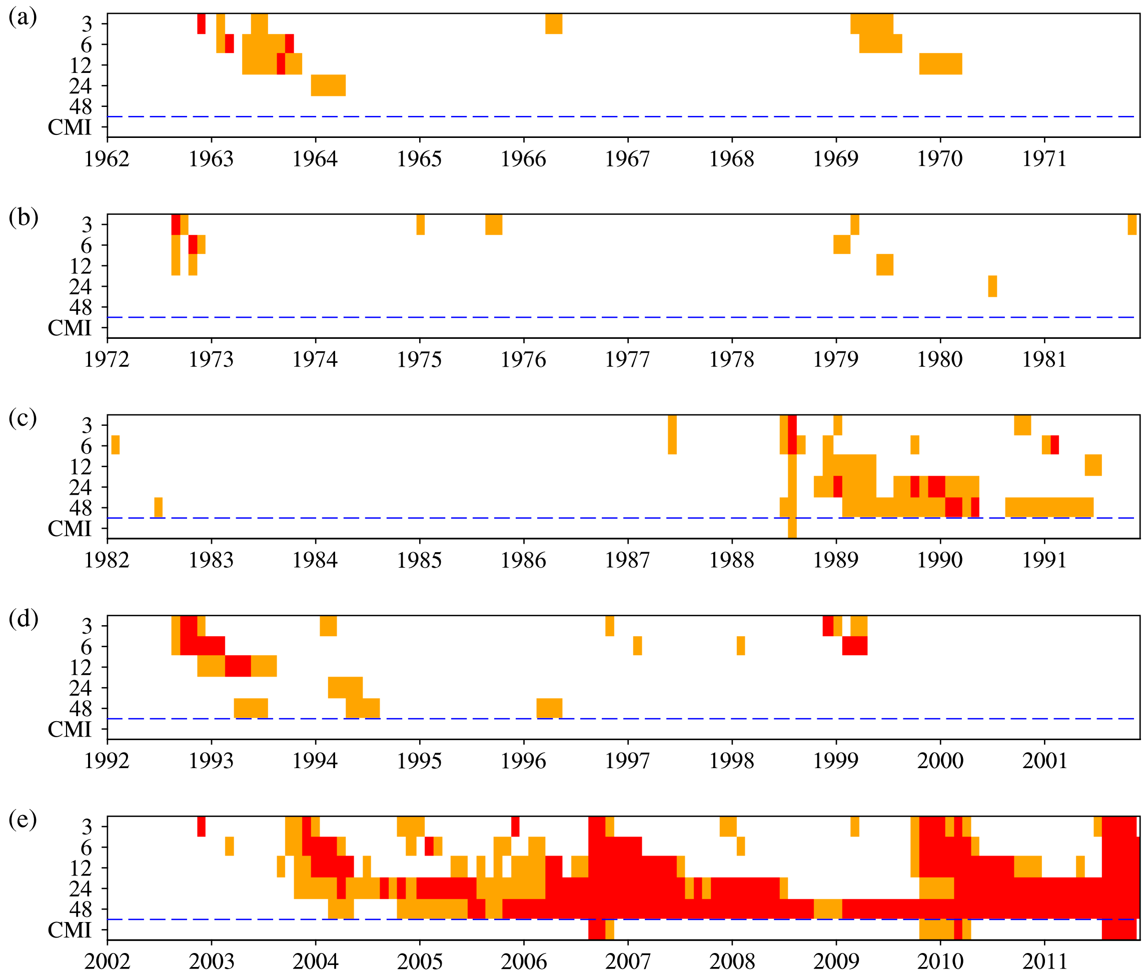

Figure 3. Occurrence of severe (yellow) and extreme (red) droughts based on SPEI at the time-scales of 3, 6, 12, 24 and 48 months (y-coordinate), along with that of S-type (yellow) and E-type (red) droughts based on CMI in the period of 1961–2011. The x-coordinate represents the periods of (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, and (e) 2002–2011.

the near-normal or even moist conditions of another time-scale do help alleviate drought tensions. However, the simultaneous occurrence of extreme droughts at multiple time-scales is likely to reinforce the damage that would result from a single-time-scale event and thus render mitigation actions ineffective.

Based on the above thoughts, we propose a metric based on SPEI, called the Comprehensive Multiscalar Indicator (CMI), to consider the combined effects of wet/dry states at different time-scales. We define 'super-drought' status as SPEI below −1.5 at all time-scales of 3, 6, 12, 24 and 48 months, denoted by SE-type:

> SE-type: occurs when the SPEI at all time-scales of 3, 6, 12, 24 and 48 months is below −1.5

The SE-type is further divided into two classes, called 'S-type' and 'E-type', defined as follows:

> S-type: occurs when the SPEI at all time-scales of 3, 6, 12, 24 and 48 months is below −1.5, with at least one greater than −2.
> E-type: occurs when the SPEI at all time-scales of 3, 6, 12, 24 and 48 months is below −2.

By definition, the E-type drought is self-evidently more serious than the S-type, and it is not hard to prove that S-type and E-type are mutually exclusive and that their union is the same as SE-type. The reason for choosing the time-scales of 3, 6, 12, 24 and 48 months to construct the indicator is that these represent the time required for precipitation shortages to affect the five types of usable water sources (McKee *et al.*, 1993). CMI provides a simple and reliable means to detect whether the meteorological, agricultural and hydrological droughts reach their extreme peaks synchronously or not. In addition, there is generally an extremely low probability of either S-type or E-type drought.

4. Analysis

Since the three most calamitous droughts are clustered within the last decade, we concentrate mainly on the fluctuations of SPEI and CMI from 2002 to 2011. As shown in Figure 3, this massive drought period can be traced back to the autumn of 2003, after which a series of short-term dry events frequently hit SWC and were crucial to invoking long-term drought. On the one hand, it is in late 2005 that long-term drought became established because of the slow responses of the hydrological system. From the beginning of 2005 to mid-2006, on the other hand, SWC continued to be exposed to hydrological drought, although the severity of short-term drought, as indicated by the 3- and 6-month SPEI values, diminished owing to transient ample rains.

However, conditions over SWC deteriorated in the summer of 2006, when extreme droughts at multiple time-scales coincided, as reflected by CMI. As mentioned in the introduction, precipitation anomalies are frequently employed to quantify drought severity over SWC, but these are not a good indicator of super-events since monthly or seasonal precipitation anomalies can reflect only short-term conditions that are closely tied to soil moisture and crop stress. Figure 4 shows the comparison between summer precipitation anomalies in 1972 and 2006. In both cases, departures from normal June-July-August precipitation compared to 1961–1990 climatology range from −60 to −80 mm month^{-1}, with the most intense being located in Guizhou for 1972 and the east of Sichuan and Chongqing for 2006. In spite of slightly different geographic patterns, the precipitation deficits in both cases have overall similar intensities and cover broad portions of SWC. If we rely on seasonal precipitation anomalies alone, therefore, the 1972 summer drought should be of the same magnitude as that in 2006. However, Figure 3(b)

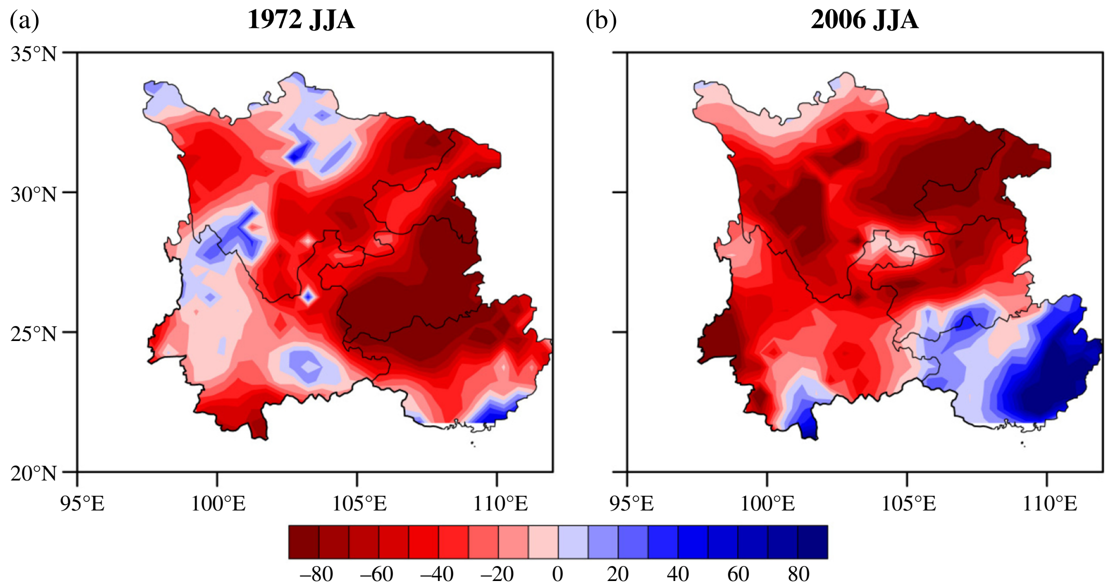

Figure 4. Spatial distribution of summer (June, July and August) precipitation anomalies (unit: mm $month^{-1}$) in (a) 1972 and (b) 2006 over Southwest China.

shows that no hydrological drought (24- and 48-month SPEI) emerged in the summer of 1972, because the summer drought in 1972 was preceded and followed by generous precipitation (figure not shown), which played a key role in suppressing hydrological drought. Consequently, no S-type or E-type drought showed up in the summer of 1972, preventing drought tensions from being far worse. In contrast, the long-term drought that had already developed before the summer of 2006, as mirrored by the 12-, 24-, and 48-month SPEI, was superimposed on the sudden hit of short-term drought to collectively reinforce the destructive effects of the drought. It should be kept in mind that the paucity of summer precipitation in 2006 was a stimulus to short-term drought rather than to hydrological drought, which had developed previously.

After the summer drought of 2006, droughts ranging from short to long time-scales recovered back to normal conditions in sequence. However, short-lived ample precipitation did little to mitigate a dry hydrological period, which persisted until the end of 2011. Therefore, the exclusive dependence on monthly or seasonal precipitation anomalies or short-term drought indices inevitably leads to the misinterpretation that the drought is over. A second wave of sustained S-type/E-type drought broke out in October 2009, due to the joint effect of lingering hydrological drought and the sudden arrival of meteorological/agricultural drought. Although previous studies documented that the drought from the autumn of 2009 to the spring of 2010 began in October 2009, hydrological conditions were extremely dry before then, and SPEI was predominantly lower than −2.0. Consequently, it is more accurate to state that October 2010 was the commencement of the joint occurrence of extreme droughts at multiple time-scales.

After the prolonged drought from the autumn of 2009 to the spring of 2010, 3- and 6-month SPEI returned to normal, whereas 24- and 48-month SPEI remained continuously in an extremely dry category. Consequently, drought tension was temporarily relieved due to the disappearance of short-term drought. However, E-type drought erupted from mid-summer to mid-autumn of 2011, which can be identified as the driest period in the last 50 years; SWC had never seen four consecutive months with meteorological, agricultural and hydrological droughts reaching extreme peaks simultaneously. In this SWC case, the S-type and E-type of drought both had a 1% probability of occurring, demonstrating that it is rare for severe/extreme droughts at multiple time-scales to occur simultaneously.

To further validate the applicability and superiority of CMI and to illuminate the mechanism responsible for the catastrophic events, Figure 5 illustrates the temporal evolution of the percentage of pixels with CMI falling in the E-type category (yellow dashed) and the SE-type (red solid) from 1961 to 2011, respectively. For comparison purposes, the time series of areal coverage of extreme drought (SPEI ≤ -2.0, yellow dashed) and severe drought or above (SPEI ≤ -1.5, red solid) are added in Figure 5. As can be seen in Figure 5(f), the percentage of area affected by S-type or E-type droughts peaked in the summer of 2006 (25%), the autumn of 2009 to the spring of 2010 (25%), and the summer of 2011 (42%), while in other periods the spatial coverage never exceeded 10%, demonstrating once again the excellent correspondence between CMI and actual super-drought events. In contrast, if we inspect the drought coverage calculated from the 3-month SPEI, region-wide droughts are not peculiar to the summer of 2006, the autumn of 2009 to the spring of 2010, and the summer of 2011, since the severe/extreme droughts over other time slices including January 1963 to June 1963, December 1968 to January 1969, etc., are as widespread as the recent three worst droughts. Likewise, the spatial extents with respect to the three super-droughts are similarly not outstanding if we rely on SPEI at any other individual time-scale.

5. Conclusion and discussion

During the last decade, SWC has experienced three mega-droughts, which occurred in the summer of 2006, the autumn of 2009 to the spring of 2010, and the late summer of 2011, all of which caused considerable losses including crop failure, shortage of drinking water, ecosystem destruction, health problems, and even deaths. Despite significant SWC drought-related research, the essential feature behind super-drought events is not yet fully understood and traditional drought indices as well as precipitation fail to recognize them, due to a lack of integrated treatment of drought.

Based on the basic idea that extreme droughts in different components of water resources can take place simultaneously, exerting synergistic stresses on local residents and ecosystems, a qualitative metric, the Comprehensive Multiscalar Indicator (CMI), is proposed to detect whether the severe/extreme droughts at multiple time-scales occur alone or in concert. Re-examination of droughts in SWC demonstrates that super-extreme droughts are characterized by a combination of extreme dry states in multiple components of water resources, which is the intrinsic distinction between these and more moderate droughts. Furthermore, the three super-droughts over the last decade can be successfully captured by CMI, without including trivial events, confirming its powerful utility for tracking super-extreme droughts.

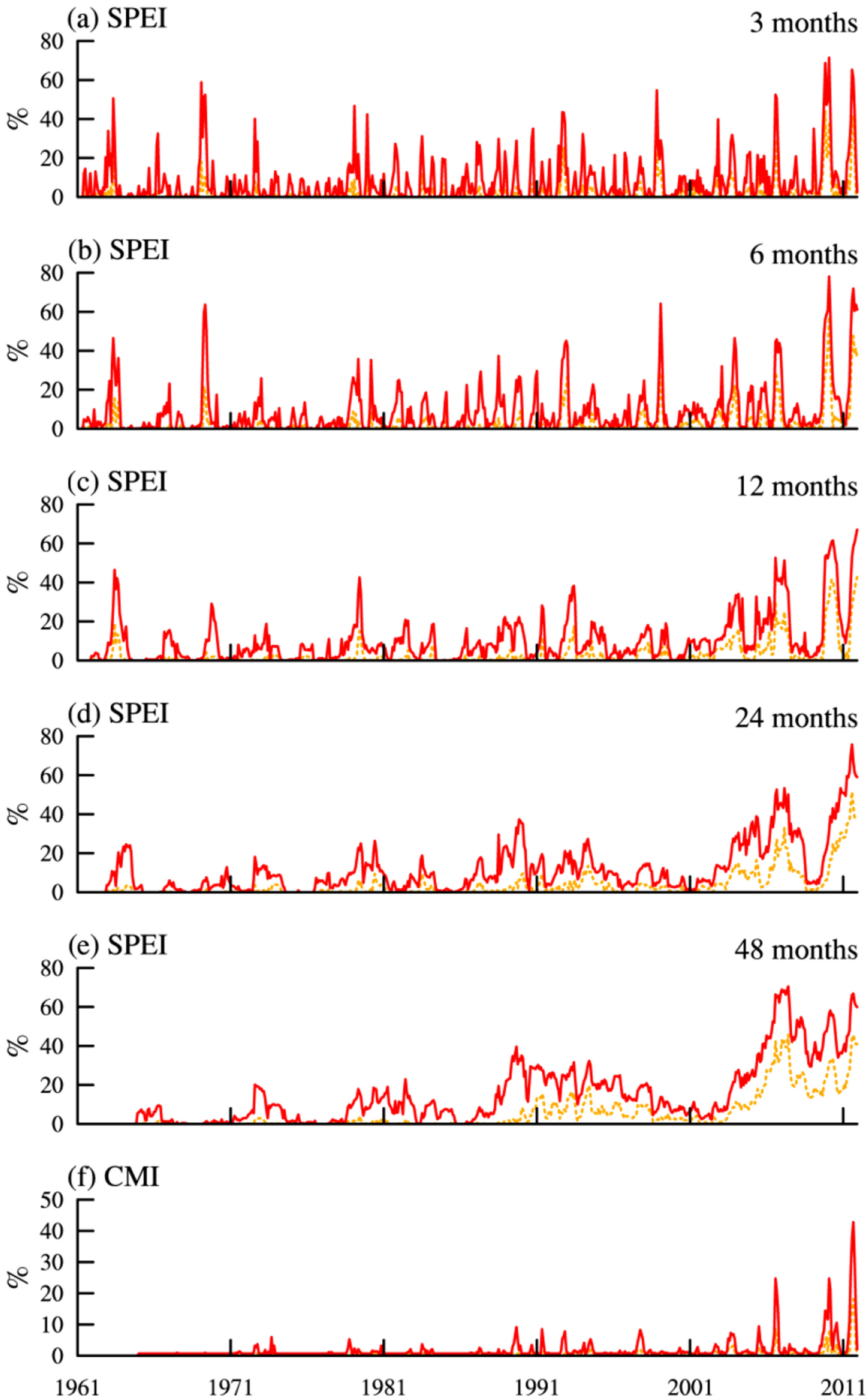

Figure 5. Temporal evolution of the percentage of land area under extreme drought (yellow) and at least severe drought (red) at the time-scales of (a) 3, (b) 6, (c) 12, (d) 24 and (e) 48 months, and (f) that under E-type (yellow) and SE-type (red) from 1961 to 2011.

Finally, there are several important points to discuss. (i) Despite the fact that CMI is created based on SPEI, it has its own unique behaviour, which differs from the variability of SPEI. (ii) Although CMI is developed in this study to integrate dry/wet states at multiple time-scales into an integrated measure, the investigation of drought at various time-scales does make sense because we still need to identify different drought types, in other words, which particular systems of usable water resources are under drought conditions. As such, it is important to emphasize that CMI should be viewed as a complement to SPEI and not a substitute for it. Consequently, collaborative use of SPEI and CMI will provide better understanding and monitoring of drought phenomena. (iii) In this study, the research domain is restricted to SWC, in which the essential feature of super-extreme droughts and the excellent performance of CMI are illustrated. However, we have validated our findings and CMI in other parts of the world beyond SWC and found they still worked successfully. Further investigations are currently underway and will be reported in a forthcoming article.

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