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Drought in Southwest China: A Review

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Abstract The clustering of severe and sustained droughts in Southwest China (SWC) during the last decade has resulted in tremendous losses, including crop failure, a lack of drinking water, ecosystem destruction, health problems, and even deaths. Various attempts have been made to explore the variability and causes of drought in SWC. Here, the authors summarize and integrate this accumulated but fragmented knowledge. On the whole, general agreement has been reached on the evolution of drought in SWC, which has become more frequent and intense during the past 50 years and is projected to continue throughout the 21st century. However, it is unclear and even disputable as to what and how sea surface temperatures and circulation oscillation patterns affect the drought condition. Meanwhile, the presence of strong nonlinearity places considerable challenges in both understanding and predicting drought in SWC. Therefore, much remains to be learned concerning the mechanisms responsible for drought disasters in SWC and accurate forecast practice. In addition to pursuing research on factors and processes involved in drought formation, above all, there is an urgent need to develop appropriate strategies and plans for mitigating the threats of drought.

Keywords: drought, Southwest China, historical change, future scenario, mechanism

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1 Introduction

Southwest China (SWC) covers an area of approximately 1.23 million km^2, or 12.9% of China, with latitude and longitude ranging from 22°N to 32°N and 98°E to 110°E, respectively, and comprises four provinces and one municipality: Sichuan, Guizhou, Yunnan, west of Guangxi and Chongqing. SWC is one of the most densely populated regions in China, accounting for an estimated 1/6 of the nation's total, and is also the main grain producing area, providing approximately 16% of the national food supply. SWC has abundant precipitation of about 1200–1800 mm per year on average; meanwhile, it contains headwaters of many important rivers, including the Yangtze, Lancang, and Nujiang, which provide as much as 46% of China's available water resources. Despite being located in the humid climate zone, exceptional and sustained droughts have frequently hit SWC in the last decade, with the summer of 2006, the autumn of 2009 to the spring of 2010, and the summer of 2011 being record-breaking events (Wang et al., 2014). According to statistics reported by the Chinese government, severe drought together with high temperatures during summer 2006 caused water scarcity for at least 18 million residents, crop failure on 311300 ha of land, and economic losses of 11.74 billion yuan (Li et al., 2009). During the long-lasting drought from autumn 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; Qian and Zhang, 2012; Yang et al., 2012b). One year later, the drought in the summer of 2011 affected a combined 5.86 million ha of crops, leaving a total of 9.17 million livestock and 12 million people short of drinking water (Sun et al., 2012; Wang et al., 2012). All of these super droughts constitute devastating and far-reaching threats to agriculture, water availability, ecosystems (Zhang et al., 2012a, b), the economy, and society (Ye et al., 2012). Besides the negative effect of drought, the complex topography, erosion, deforestation, and poor water management have exacerbated the worst drought events in SWC (Qiu, 2010).

Before massive droughts over SWC initiated in 2006, studies of drought/flooding across eastern China and Northwest China were hot topics among the research community (e.g., Huang, 2004; Zhou et al., 2006, 2012; Zhou and Chan, 2006; Chen et al., 2009, 2013a, b; Wei and Wang, 2013; Li et al., 2014a; Qu et al., 2014). During recent years, devastating droughts in SWC have attracted great concern from both the Chinese government and the academic sector. To date, considerable efforts have been expended on surveying the characteristics as well as establishing the physical causes of droughts in this hotspot region. Nevertheless, the relevant literature remains fragmented. Therefore, in this review paper, we gather and integrate the past achievements in understanding the multiple aspects of drought in SWC, and highlight the pend-

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ing obstacles and knowledge gaps that need to be addressed in future work.

The remainder of the paper is organized as follows: In section 2, we review the historical change of drought in SWC from an observational perspective, along with future projections based on simulations by climate models. After describing the basic characteristics of the variability of drought in SWC, the suggested causes of drought in the region are summarized in section 3. Finally, section 4 provides concluding remarks and suggests directions for future research.

2 Historical and future projected changes of drought in SWC

This section provides the current knowledge from historical and future perspectives regarding drought in SWC. He et al. (2011), Zhang et al. (2013a), and Li et al. (2014b) all detected the spatiotemporal signatures of dryness-wetness variations in SWC from 1960 to 2009 and, despite the different drought metrics employed, the generally consistent finding was that drought events in SWC have increased in both intensity and frequency during the past half a century, induced by the combined effect of decreasing precipitation and rising temperature. Wang and Chen (2012) examined the multiscalar variability of drought over SWC in long records starting from the early 20th century and found dramatic interannual variability superimposed on interdecadal oscillations without a pronounced long-term trend. Therefore, the trend towards increasing drought in the last 50 years may indeed reflect a phase transition associated with multi-decadal variability. Although current droughts are extremely serious, it is in fact not the worst period in a long-term context because the drought episodes centered around the year 1940 experienced the same intensity and duration. Other dry periods with less detrimental effects included the 1960s and 1990s, while very or extremely humid conditions were recorded in 1910–30, the 1950s, and 1967–70. In addition, other decades were characterized by climatic stability, with less intensive and shorter dry or humid periods. Recently, Ji et al. (2015) extended the analysis back to 1500 A. D. with the help of yearly charts of dryness-wetness in China for the last 500 years, a reconstruction product on the basis of China's official historical documents. On the centennial scale, an abrupt increase of drought disasters was found during the 20th century compared to the past four centuries. However, it should be noted that there remains substantial uncertainty with respect to the proxy database inferred from chor-ography, indicating that interpretations of reconstructed drought variability should be treated with caution. Despite significant efforts made to place drought in SWC in a historical context, as Wang et al. (2015a) pointed out, it remains unclear as to why the recent super droughts are historically unprecedented during the past 50 years and what is the essential feature behind them. These failures stem from the absence of an integrated approach to quantifying drought and its associated indexes, which is crucial for understanding the mechanisms responsible for super droughts and for distinguishing such droughts from those of less consequence. A new metric, called the Comprehensive Multiscalar Indicator (CMI), was developed to consider the combined effects of the wet/dry state at different timescales. Reexamination of droughts in SWC illuminates the essential feature of super droughts events—a combination of multiple stresses on water resources and highlights the utility of CMI.

As we know, climate change poses a significant challenge to human survival and development, especially for underdeveloped regions. Apart from understanding historical evidence, it is of vital importance to assess possible future scenarios of drought risk under the background of global warming. Such knowledge will be helpful for the state and local government in preparing advanced mitigation and adaptation strategies. Wang et al. (2014) evaluated potential future changes in drought over SWC under the CMIP5 (Coupled Model Intercomparison Project Phase 5) framework. Towards the end of 21st century, precipitation and evaporation are both expected to increase, resulting from intensified water vapor transport from the Bay of Bengal and the joint effect of elevated temperature and surface net radiation, together with reduced relative humidity, respectively. In comparative terms, the increasing rate of evaporation outweighs that of precipitation, producing an overall drying tendency in SWC (Fig. 1). Furthermore, we see that not only will incidences of severe and extreme drought increase dramatically in the future, but extremely wet events will also become more probable. It is also noteworthy that the future drought risk in SWC is nearly twice that in other parts of the country (Wang and Chen, 2014). In light of the current impacts and future threats of drought disasters in SWC, it is imperative to take measures to improve our ability to cope with such change, including water management solutions, adjustments to cropping structures, soil protection, and so on.

3 Mechanisms responsible for drought in SWC

Based on the above arguments, the variability of drought in SWC at varying time scales becomes clear, but the physical mechanisms responsible remain elusive. In general, the maintenance of deficient precipitation over affected areas is often regulated by persistently abnormal sea surface temperature (SST) and the resulting atmospheric conditions. Therefore, many studies have been conducted to explore the critical pattern of SST and synoptic systems with significant influence on the lack of rainfall in SWC. Besides, drought is often enhanced by land-atmosphere coupling, which plays a significant role at a more local and on shorter time scales. Figure 2 summarizes the factors currently recognized as possibly being engaged in drought formation over SWC.

At present, the vast majority of studies on the topic have been carried out with a focus on particular droughts, such as those that occurred in summer 2006, autumn 2009 to spring 2010, and summer 2011. Yang et al. (2008), Li

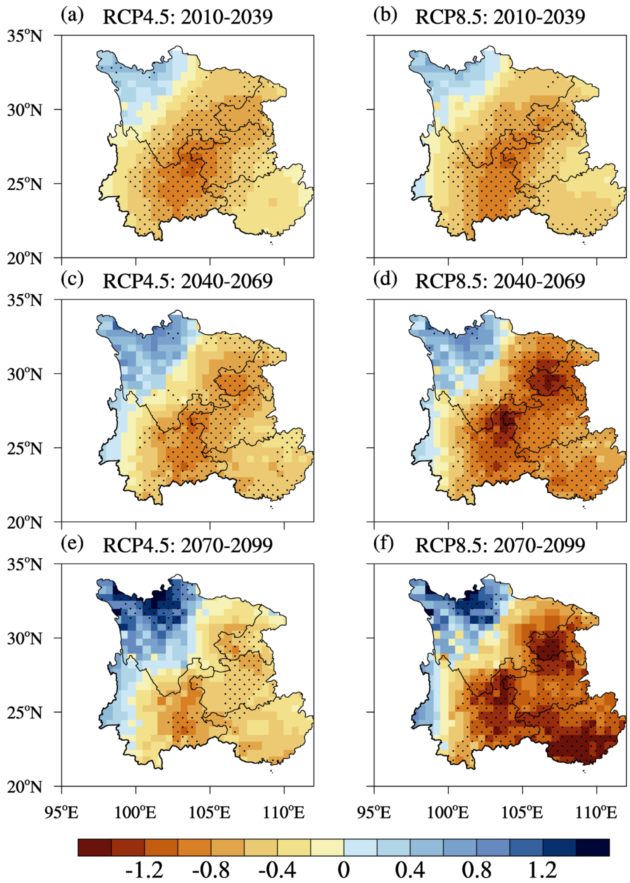

Figure 1 Spatial pattern of projected dryness-wetness changes from the reference period (1961–90) to 2010–39 (top row), 2040–69 (middle row), and 2070–99 (bottom row) under RCP4.5 (left column) and RCP8.5 scenarios (RCP: Representative Concentration Pathway). Brown shading indicates the drying tendency, while blue shading denotes the opposite. Refer to Wang et al. (2014b) for further details.

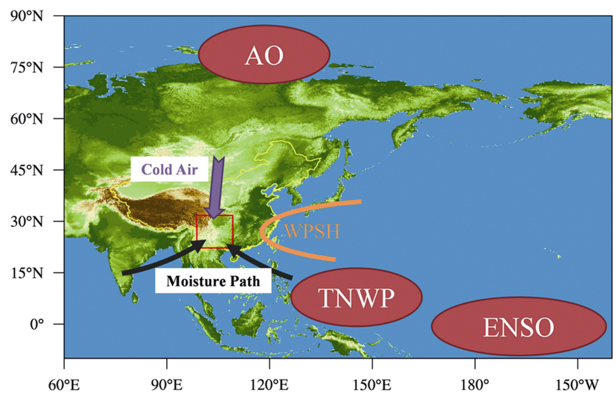

Figure 2 Schematic diagram of the important candidates that might be involved in drought formation over Southwest China. The yellow line is China's border, while the red box denotes the SWC region. TNWP stands for the tropical Northwest Pacific, ENSO, WPSH, and AO stand for El Niño Southern Oscillation, Western Pacific Subtropical High, and Arctic Oscillation, respectively.

et al. (2009), and Liu et al. (2009b) all noted that, during summer 2006, the western Pacific subtropical high (WPSH) strengthened, with its ridge line shifting northward and extending westward, and the Tibetan high lay eastward. The two highs then merged into a stable belt of continental high pressure aloft in the middle and upper troposphere. Under the control of high pressure, downward airflows prevailed in SWC and moisture supply from the Bay of Bengal and South China Sea to this region was blocked, as evidenced by anomalous water vapor flux from the northeast to the southwest, and an associated divergent center situated in the Sichuan-Chongqing region (Liu et al., 2009a). Further investigation showed that a stronger heat source induced vigorous convective activities over the western Pacific in summer (Peng et al., 2007) and less snow cover over the Tibetan Plateau in the preceding winter and spring (Zou and Gao, 2007), give rise to the amplification of the WPSH and the Tibetan high, respectively. Moreover, accompanied by a weak blocking high in the Ural Mountains and a shallow East Asian trough, the midlatitudes were dominated by stronger zonal circulation than usual, which hindered the southward intrusion of cold air into SWC. Consequently, the large-scale configuration of the subtropical and midlatitude circulation pattern during summer 2006 was not favorable for the convergence of warm-moist air from the south and cold-dry air from the north, and thus severe drought developed.

Related with the autumn 2009 to spring 2010 drought, several potential climatic candidates have been identified. At the local scale, SWC was characterized by a lack of moisture and warmer air temperature throughout the lower and middle troposphere, which together made it hard for the air to become saturated and thus also made it hard for rain to form (Lu et al., 2011; Yang et al., 2012b). Meanwhile, significant anomalous descent was observed in SWC. Even so, what and how did remote forcing affect the regional thermodynamic characteristics? Yang et al. (2012b) reported a significant positive correlation between the Arctic Oscillation (AO) index and precipitation in SWC, indicating that a negative phase of the AO may bring drought to the region. Accordingly, Barriopedro et al. (2012), Huang et al. (2012), and Yang et al. (2012b) all noted that, in winter of 2009/2010, the AO index amounted to its lowest value since the mid-20th century, which brought the track of cold waves eastward with coincident reduced northerly flow of cold air into SWC, as mirrored by pronounced low temperature overwhelming the eastern half of China. Meanwhile, SWC also suffered from deficient moisture supply: during autumn 2009, an anomalous cyclone over the South China Sea impeded water vapor transport from the western Pacific and the Bay of the Bengal; during the subsequent winter, a flat-shaped south branch trough (also called the India-Burma trough) diverted water transfer to the far east before penetrating inland towards SWC (Wang and Li, 2010; Zhang et al., 2011; Barriopedro et al., 2012). Furthermore, Huang et al. (2012), Yang et al. (2012b), and Zhang et al. (2013b) all assumed oceanic warming in the equatorial central Pacific that began around June and matured in November, known as El Niño Modoki, to be the principal external forcing in shaping East Asian circulation pattern anomalies. Specifically, El Niño Modoki induced a strongly anomalous cyclone over the west North Pacific during autumn 2009 (Zhang et al., 2013b), while a substantial westward extension of the WPSH (Yang et al., 2012b) along with an anticyclone over the South China Sea (Huang et al., 2012) occurred during winter 2009/2010, all of which were conducive to a strong decline in water vapor transport to SWC. Conversely, however, Jiang and Li (2010) and Yang et al. (2012a) both argued that the drought during winter 2009/2010 did not arise from the impact of El Niño, owing to the fact that the SST anomaly composite for extreme rainfall deficit years resembled a La Niña pattern. Another controversial aspect is the effect of the Indian Ocean (Huang et al., 2012; Zhang et al., 2013b). In summary, studies are generally consistent in the AO playing a critical role in the extreme drought condition of 2009/2010, but it remains an open question as to whether El Niño Modoki or the Indian Ocean make the greatest contribution. We elaborate on this further later in the paper. Additionally, Li et al. (2013) demonstrated the importance of antecedent soil moisture anomalies in their simulation, showing that reduced soil moisture in autumn led to decreased precipitation in the subsequent winter via positive feedback loops.

With respect to the 2011 summer drought, Sun et al. (2012) and Wang et al. (2012) concluded that a weakened water vapor supply and prevalent descending motion over SWC yielded the severity and persistence of the drought. Such a pattern is quite similar to the atmospheric configurations noted during the previous event in summer 2006. However, the WPSH exhibited contrasting characteristics in summer 2006 and 2011 in terms of its zonal extent. Li et al. (2014c) revealed that the WPSH stretched westward in 2006 but withdrew eastward in 2011, indicative of its possible nonlinear behavior.

The case studies summarized above are indispensable but can sometimes be misleading, because of their very narrow focus. Recent studies have endeavored to provide a more general description of the synoptic and SST conditions, as opposed to specific examples, offering deeper insight into the causes of drought. Feng et al. (2014) studied the teleconnected causes of drought in SWC during its dry season (November to March), and considered SST anomalies in the tropical Pacific and North Atlantic to be the main drivers for drought. During La Niña years, enhanced heating over the Maritime Continent provokes anomalous downward motion over SWC through the connection of local Hadley circulation; in the presence of an ENSO-neutral status, a negative-phase North Atlantic Oscillation (NAO) plays a crucial role by exciting a large-scale wave train that leads to an anomalous anticyclone in SWC. Xu et al. (2012) focused on the asymmetric relationship between the NAO and SWC precipitation in boreal winter, disclosing that the negative phase of the NAO generates insufficient precipitation over SWC, while the relationship between them is not significant for the opposite phase.

Regarding autumn drought, as suggested by Wang et al. (2015b), it is primarily the tropical Northwest Pacific (NWP) SST that exerts an influence on SWC; moreover, the three key dynamic processes linked to drought in SWC in response to a warm NWP have also been elucidated based on both observational diagnosis and numerical experiments. Therefore, it is evident that there is no preference for drought during the dry season to be correlated to the El Niño portion of ENSO. However, as mentioned, the 2009/2010 drought was attributed to El Niño Modoki by Huang et al. (2012), Yang et al. (2012b), and Zhang et al. (2013b). So, why are there such conflicting attitudes towards the effect of ENSO? One possible explanation to reconcile these disparate findings is that the response of drought and its associated circulation pattern to ENSO forcing is rather nonlinear. If a nonlinear association exists, it is probable for individual events (i.e., the 2009/2010 drought) to be influenced by a specific El Niño episode, with its distinct features in terms of intensity and location, even though there is no overall correspondence between them.

Also recall that a strong and westward extension of the WPSH during summer 2006 is believed to have promoted the dry condition over SWC. Following the linear perspective, a weak and eastward retreat of the WPSH implies plentiful precipitation in SWC. However, Li et al. (2009) examined the strength indices and western-most points of its ridge line corresponding to severe drought in different years, and revealed that the WPSH patterns associated with marked positive and negative rainfall anomalies in SWC are not opposite to each other. Instead, either stronger with a westward shift or weaker with an eastward shift of the WPSH can result in inadequate precipitation over SWC, implying a nonlinear response of SWC precipitation to the amplitude and zonal deviation of the WPSH during summer. Nevertheless, a common feature shared by almost all drought events is the poleward displacement of its ridge line (Li et al., 2009; Liu et al., 2009b).

Lastly, but importantly, the worsening drought risk in SWC is not only a natural process, but also the result of inappropriate human intervention. Extensive human activities have been exerting increasing impacts on the fragile environment of the region, including the degradation of vegetation, deforestation, soil erosion, and excessive consumption of water resources. When anthropogenic impacts work in tandem with natural disasters, drought conditions can intensify and perpetuate. Mu et al. (2010) studied the effects of human activity on severe drought in SWC, but it is beyond the scope of this review to go into their findings in detail.

4 Conclusion and future perspective

Starting around 2006, a sequence of extreme droughts have struck SWC, resulting in tremendous losses including crop failure, a lack of drinking water, ecosystem destruction, health problems, and even deaths. Enormous amounts of research effort have been dedicated to investigating the variability and causes of droughts in SWC. In this review, we first document the basic characteristics, encompassing historical changes and future scenarios, of dryness-wetness variation in SWC, and then summarize the proposed mechanisms responsible for drought. On the one side, clear agreement has been achieved on the spatiotemporal evolution of drought in SWC, which has become more frequent and intense during the past 50 years and is projected to continue throughout the 21st century. On the other side, however, although our understanding of the causes of drought in SWC has progressed a great deal, evolving from case studies to more generalized theory, many controversies and open questions remain. Hence, there is much left to be learned about the mechanisms that trigger drought in SWC. Based on this review of the literature, the key issues and challenges to be addressed in the future are highlighted as follows:

(1) Role of SST (particularly ENSO) with associated teleconnections. There is great uncertainty as to which SSTs and induced atmospheric circulation anomalies cause drought or flood conditions in SWC. Detailed investigations need to be made to determine the exact impacts of SSTs. In particular, since ENSO is known to heavily disrupt normal weather conditions in many parts of the world, it is essential to ascertain the role and effect of ENSO, be it of the canonical or Modoki type. Besides, previous results are suggestive of a possible nonlinear influence of ENSO, depending on its intensity and location, on SWC, which deserved further attention.

(2) Strong nonlinearity. The SST and circulation patterns tied to the fluctuation of SWC precipitation are typically complicated, with already reported nonlinear influences of the WPSH and ENSO at play. Consequently, a simple linear technique, such as correlation, regression or composite analysis, is not applicable. The presence of nonlinear relationships invokes appreciable difficulties in understanding the mechanisms involved.

(3) Predictability and prediction. The ultimate goal of understanding the mechanisms and processes underlying drought variability is to develop skillful prediction. Further, the ability to predict drought accurately relies on our knowledge of sources of predictability. However, little is currently known about potential predictors of drought in SWC. Moreover, as a consequence of strong nonlinearity, it is challenging to build effective prediction methods because current climate models are incapable of capturing both the position and intensity of SST and circulation anomalies.

The scope of future work is not limited to the key issues outlined above. In particular, the contribution from land surface processes, both locally in SWC and remotely in the Tibetan Plateau, has not yet been investigated. Obviously, more research is needed in the future to reveal the potential candidates that contribute to drought in SWC. Therefore, the only way to address drought-related problems in SWC is via the concept of the climate system.

Finally, regardless of whether or not improvements will be made to our understanding and forecasts of drought in SWC, it is urgent to implement planning and mitigation strategies in order to reduce the adverse impacts when drought occurs.

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