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Characteristics of drought in Southern China under climatic warming, the risk, and countermeasures for prevention and control

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Abstract

The temporal and spatial characteristics of drought disasters in Southern China were analyzed by using the daily observation data from 252 meteorological stations and drought disaster data in 14 provinces, autonomous regions, and municipalities of Southern China during 1961–2015. The characteristics of drought disaster risk were determined, and the countermeasures for prevention and control were also suggested. The results showed that the annual precipitation fluctuated and has no obvious linear trend in Southern China in the past 55 years. However, the average annual precipitation decreased significantly and its oscillation amplitude is increasing in the early twenty-first century. The annual average temperature exhibited a significant upward trend in these years in the research area. The increasing rate was even higher than the global means. The temperature has increased since 1976, and an abrupt change was occurred in 1997. Area with high risk of drought was concentrated mainly in Southwest China. With the climatic warming, the drought frequency and intensity and the drought-affected areas have been increasing, as well as the risk of drought disaster. The risk area of secondary highest drought disaster expanded dramatically after 1997. In the future, the occurrence of droughts may increase in Southern China. Therefore, it is necessary to enhance risk management for drought disasters by implementing eco-environmental modifications in the vulnerable areas, as well as ensuring food security in the agricultural production areas, addressing the uneven spatial and temporal distributions of water resources and the discrepancy between supply and demand, and enhancing the prevention and control of drought disaster risk.

1 Introduction

Humans have always been affected by disasters caused by drought. The global environment is vulnerable to drought disasters and these natural disasters have occurred throughout the world (Zhang et al. 2015d; Mishra and Singh 2010).The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) noted that in the twenty-first century, the global water cycle will exhibit an uneven response to the changes caused by climate warming. Thus, there may be regional anomalies, but the differences in precipitation between humid and arid land areas, and the rainy and dry seasons will be more intense. By the end of twenty-first century, under the higher emission scenarios (PCR 8.5), the average precipitation will decrease in the dry regions located in the middle latitudes and subtropics. The estimated soil moisture will decrease at the regional to global scale. Thus, the possibility (middle credibility) of agricultural drought will increase in the current arid area (Stocker et al. 2013; Allen et al. 2012). The water cycle will accelerate further as the climate warms in the future. The water balance will also change, including plant transpiration and surface evapotranspiration. In addition, instability and risk will be increased for agricultural production (Wang et al. 2015a).

China is one of the countries where drought disasters occur frequently. The annual average drought-affected agricultural area is 2.4×10^7 hm^2. The frequency of droughts had increased

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during recent years, especially in Southern China. High and very high drought hazard occurs frequently in most parts of Southern China (Liu et al. 2015; Wang et al. 2015b; Wang et al. 2014; He et al. 2011, 2013) and the drought risk in Southwest China even exceeds the national average (Han et al. 2016). Southern China is an important commodity grain base, the persistent drought events become a serious threat to food production in this area. Since the end of the twentieth century, the frequency and intensity of agricultural drought have increased and the damage has enhanced. In 2003 and 2004, Southern China was affected by severe regional droughts. In 2006, there was a major once-in-a-century drought in the Sichuan and Chongqing areas. From 2010 to 2013, Southwest China suffered from drought for four consecutive years. From January to May in 2011, the precipitation in the middle and lower reaches of Yangtze River was the lowest compared with the same period historically in the previous 50 years. The number of non-precipitation days was also the highest since 1961 and the area influenced by drought was also the largest in the last 60 years (Huang et al. 2012; Li et al. 2015; Luo and Li 2014).

Climate warming causes damage and complicates the development of drought disasters, but it also makes the factors related to the drought disaster risk more complex and diverse (Lu et al. 2007; Neelin et al. 2006; Sheffield and Wood 2008). In particular, the comprehensive loss ratio for agricultural drought is negatively correlated with precipitation. If the annual precipitation decreases by 100 mm, the comprehensive loss ratio increases by approximately 0.76% in Southern China (Zhang et al. 2015c). In regions with low precipitation and higher vulnerability to risk, such as the Yunnan-Guizhou Plateau, the comprehensive loss ratio for agricultural drought is higher (Yao et al. 2016).

Traditional model of drought disaster defense mainly involves crisis emergency management, where public and social forces are temporarily mobilized to cope with a disaster after it occurs, rather than give some preventative measures before a drought occurs. Thus, there is often either an excessive response or a lack of a suitable response. Drought disasters will occur more frequently in the future and there is an increased need for economic and social development to cope with disasters by focusing more on risk management rather than emergency management (Zhang et al. 2014). Risk management for drought disasters must be supported by risk assessments and the development of an early warning technique for drought disasters. At present, the risk characteristics and drought disaster processes are poorly understood in Southern China. Moreover, the technical issues associated with drought risk assessments are more complex due to the variations in the drought disaster risk factors caused by climate warming (Zhang et al. 2016; Feyen and Dankers 2009; Lu et al. 2007; Tol and Leek 1999). Thus, drought disaster risk management lacks adequate technical support (Zhang et al. 2011). Therefore, there is an urgent to understand the risk characteristics of drought disasters in Southern China in a scientific manner.

In the context of climate warming, we analyzed changes in the physical characteristics associated with the drought disaster risk in Southern China. We determined the spatial and temporal variations in the drought disaster risk factors. We also developed drought disaster coping strategies as well as prevention and control measures. These measures are important for enhancing the ability to cope with and prevent disasters due to climate change.

2 Research area and data analysis method

2.1 Research area and data

Southern China covers the area south of the Qinling Mountains and Huaihe River, and the region to the east of the Qinghai-Tibet Plateau, the south part of southwest monsoon and southeast monsoon regions, including Guangdong, Fujian, Zhejiang, Hainan, Guangxi, Yunnan, Sichuan, Chongqing, Guizhou, Hunan, Hubei, Jiangxi, Anhui, and Jiangsu province. The spatial range of the area covered 97.4–123.0° E and 20.2–35.3° N. The area mainly has a subtropical monsoon climate, where the annual precipitation is mainly 600 to 2700 mm and the annual average temperature ranges from 16 to 24 °C. It can be separated into three subregions according to the meteorological and geographical differences; these are Southwest China (SWC), South China (SC), and the middle and lower reaches of the Yangtze River (MLYZ) (Fig. 1).

Daily surface meteorological observation data for the period from 1961 to 2015 were obtained from 252 national meteorological stations in Southern China. Agricultural areas affected by droughts during the period 1951–2015 were used to describe the variations of the drought disaster; the data was published by the Chinese Ministry of Agriculture.

Daily temperature and precipitation data from BCC_CSM1.1-RegCM4.0 simulations, a regional climate model RegCM4.0 one-way nested by the global model BCC_CSM1.1 (Beijing Climate Center Climate System Model version 1.1) was used to investigate the future climate change over Southern China under RCP4.5 (medium emission) and RCP8.5 (higher emission) scenarios. The simulation domain covered by RegCM4.0 includes the Chinese continent and surrounding areas, with a horizontal resolution of 50 km (see Ji 2012 for more details). BCC_CSM 1.1 is one of climate system models developed in China contribute to the CMIP5. The RegCM series of models have been employed widely in China for a number of years, particularly for climate change simulations, and due to the high resolution, the temperature and precipitation were represented well by BCC_CSM1.1-RegCM4.0. Except for parts of SWC, the deviation of simulated and observed annual mean temperature of

Fig. 1 The location of Southern China, 252 meteorological stations (red solid dot) and 3 sub-regions

1986–2005 over Southern China was between ± 1 °C, and the deviation of annual precipitations was between ± 10%, BCC_ CSM1.1- RegCM4.0 reproduces the climatology reasonably well over Southern China (Ji 2012; Gao et al. 2013; Zhang et al. 2015a).

2.2 Data analysis method

The trends in climatic elements can be calculated by (Wei 2007):

$$X_i = a + b \cdot t_i (i = 1, 2, \cdots, n) \tag{1}$$

where X_i is the climatic element, t_i represents the corresponding time for X_i, a is the regression constant, b is the regression coefficient, n is the sample size, and the variation in b is the climate trend.

The cumulative anomaly analysis method and Mann–Kendall (M–K) mutation detection method were used to detect abrupt changes in temperature (Wei 2007). Based on the original hypothesis (H_0: the assumption of an unchanged climatic series), the climatic series comprises x_1, x_2, …x_N, and m_i denotes the total number among the samples i for which x_i is larger than x_j ($1 \leq j \leq i$), where the M–K mutation detection method defines a statistic, and the significance level is α_0. If $\alpha_1 > \alpha_0$, the original hypothesis (H_0) was accepted. If $\alpha_1 < \alpha_0$, the original hypothesis was rejected and this indicated that the series had a strong increasing or decreasing trend, with an orderly curve, UF. We determined whether there was a trend in the variation using a reliability test. A reversal curve (UB) was obtained using the inverse sequence method. When the UF curve exceeded the line indicating reliability, this indicated there was an obvious trend in the variation. If the intersection of the UF and UB curves was located between the lines indicating reliability, this point was the starting point for the abrupt change.

2.3 Drought disaster risk assessment method

Drought disaster risk assessments aim to estimate the intensity and form of the drought disaster risk. Drought disaster assessment mainly involves impact assessments after a disaster, whereas drought disaster risk assessment mainly involves a preliminary assessment of the risk of possible disasters and their prediction. A drought disaster risk assessment method is established by understanding the mechanisms related to the drought disaster risk. Traditional disaster risk theory focuses on natural factors and the assessment results are relatively stable and static conclusions. In the present study, based on the disaster risk mechanisms proposed by the IPCC (Allen et al. 2012), we considered the effects of climatic variation and human activities as well as the sensitivity of disaster-prone environments in order to obtain a new conceptual model of disaster risk development (Fig. 2). The solid and dashed lines indicate direct and indirect effects, respectively. It can be seen that human activities can affect climate warming, changes on regional ecological environment (such as land utilization), and the coping and resilience, i.e., the disaster prevention and mitigation capacity. Abrupt climate change and change in either the mean state of the climate or in its variability will affect the disaster-causing factor and thus affect the drought risk. And climate change and biological evolution and community succession will make the distribution of the human and biological changed, and then impact the exposure and vulnerability of disaster-bearing body which will directly affect the drought risk. In addition, the cooping and resilience ability has indirectly effect on water resource environment, and geological and geographic environment, thus affect the sensitivity of disaster-prone environment, and then affect the drought risk. After introducing the effects of climatic variations and human activities, the conceptual model objectively characterized the mechanisms related to the drought disaster risk by reflecting the variability and dynamic characteristics of the drought
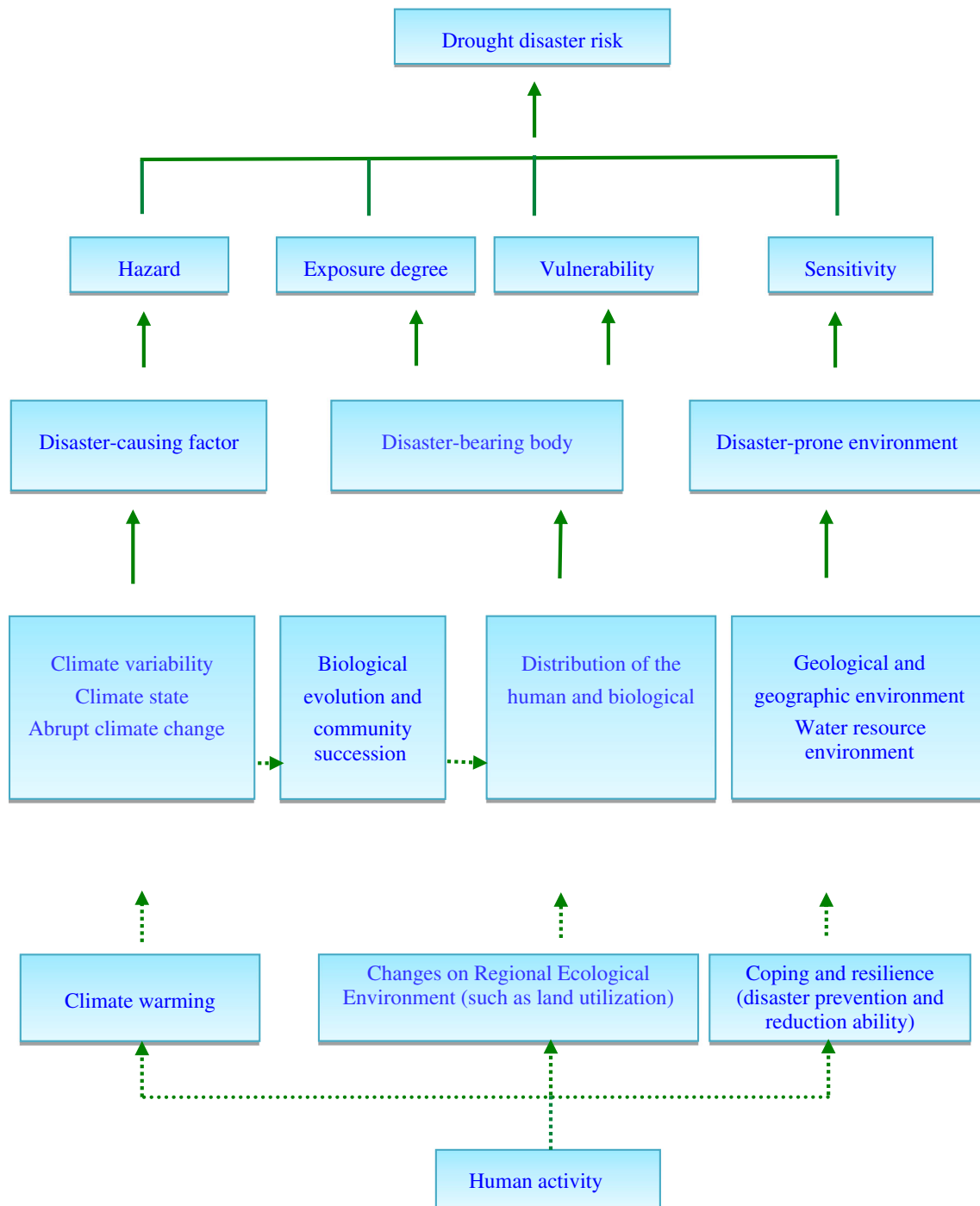
Fig. 2 Conceptual model of the drought disaster risk mechanism

disaster risk. The characteristics of the drought disaster risk in the conceptual model are more scientific and objective, so they are more similar to the actual characteristics of the drought disaster risk.

According to the conceptual model of drought disaster risk formation, the drought disaster risk system can be decomposed into the hazard due to a disaster-causing factor (h), the exposure degree or vulnerability of the disaster-bearing body (e), and the sensitivity of the disaster-prone environment (s), where the drought disaster risk index = h∩e∩s. The formula for the drought disaster risk can be constructed as follows:

$$R_d = f(h, e, s) = f1(h) \times f2(e) \times f3(s) \tag{2}$$

The analytic hierarchy process was used to decompose the drought disaster risk elements. The basic principle of

elemental decomposition requires that the separated elements should be independent of each other. Only the independent variables can be separated, so the solution is the product of the independent variable functions. Thus, the drought disaster risk assessment method is as follows:

$$R_d = H_d \cdot E_b \cdot V_e \cdot V_f \cdot P_c \qquad (3)$$

where Rd is the drought disaster risk, Hd is the intensity and probability of a drought disaster-causing factor, Eb is the exposure degree of social or physical disaster-bearing body (considering the natural environmental conditions), Ve is the vulnerability of the disaster-bearing body, Vf is the sensitivity of the disaster-prone environment, and Pc is coping and resilience (disaster prevention and reduction ability). The assessment models were established according to the weighted comprehensive assessment method (Yao et al. 2016; Wang et al. 2015b).

3 Climatic variations and drought disaster risk characteristics

3.1 Background analysis of climatic variations

3.1.1 Variations in temperature and precipitation

Temperature increased significantly (0.192 °C per decade) in Southern China as a whole during 1961 to 2015, and the overall increase was higher than global means (Mishra and Singh 2010). The cubic function of the average temperature departure decreased slightly in the 1960s, but then increased continuously from the late 1970s (Fig. 3a). The fitted equation for the cubic function was $y = -0.00003 \times ^3 + 0.0033 \times ^2 - 0.0747 \times - 0.0625$. After linearization, the multiple correlation coefficient $R = 0.806$ ($P < 0.001$). By taking the derivative of the cubic function and setting $dy/dt = 0$, we found that the deviation in the temperature increased continuously after 1975. Annual precipitation increased but the linear trend was not significant during 1961 to 2015. The maximum annual average precipitation was 1530.7 mm in 1973. And the minimum was 1095.8 mm in 2011(Fig. 3b).

Characteristic of interdecadal variability of temperature and precipitation shows that the average temperatures exhibited negative departures with an average value of -0.4 °C before the 1980s. Subsequently, the departures were ≥ 0 °C, while the coefficient of variation and the oscillation amplitude of temperature also increased. In the 1960s, the regional average precipitation was much lower and the anomalous percentage for the regional average precipitation was -2.5%. In addition, the coefficient of variation for the regional average precipitation was 6.9%. During the 1970s to 1980s, the average precipitation was relatively low. In the 1970s, the anomalous percentage for the average precipitation was -0.5% and the coefficient of variation was 8.3%. In the 1980s, the anomalous percentage for the average precipitation was -0.7% and the coefficient of variation was 6.3%. The average precipitation was highest in the 1990s, where the anomalous percentage for the average precipitation was 2.5% and the coefficient of variation was 4.4%. During the first 10 years of the twenty-first century, the average precipitation was lower, where the anomalous percentage for the average precipitation was -1.8% and the coefficient of variation was 8.3%. From 2010 to 2015, the average precipitation was also low and the coefficient of variation was high. Therefore, in the early twenty-first century, the average precipitation was obviously lower in the Southern China and the inter-annual oscillation amplitude of the average precipitation increased (Table 1).

To further understand the increases characteristic of temperature in Southern China during the 55-year period, we employed the cumulative departure curve method and M–K mutation detection method.

The changes in the cumulative temperature departure curve for Southern China (Fig. 4a) showed that during 1961 to 2015, the cumulative temperature departure exhibited an obvious "V" shape, where it decreased first from 1961 to 1996 and then increased from 1997 to 2015. The threshold point for the temperature increase was preliminarily determined as around 1997.

The M–K mutation detection curve for temperature (Fig. 4b) showed that during 1961 to 2015, the order statistic UF for the temperature departure curve began to increase continuously after 1976. In the early twenty-first century, the temperature substantially exceeded the critical significance level ($u_{0.05} = 1.96$,
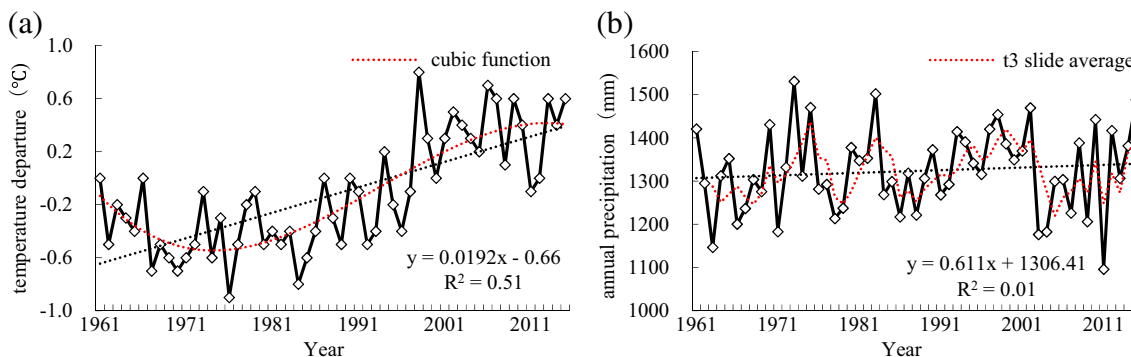

Fig. 3 Changes in temperature (**a**) and precipitation (**b**) during 1961–2015 in Southern China

Table 1 Temperature departure and anomalous percentages for precipitation during each decade in Southern China

Years	Temperature		Precipitation	
	Departure (%)	Coefficient of variation	Anomalous percentage of precipitation (%)	Coefficient of variation
1961–1970	− 0.4	1.6	− 2.5	6.9
1971–1980	− 0.4	1.5	− 0.5	8.3
1981–1990	− 0.4	1.5	− 0.7	6.3
1991–2000	0.0	2.3	2.5	4.4
2001–2010	0.4	1.1	− 1.8	8.3
2010–2015	0.4	1.6	− 0.3	9.2

$P = 0.05$) and even the extremely high significance level ($u_{0.001} = 3.29$, $P = 0.001$). Therefore, the increasing trend in the temperature in Southern China passed the significant test with an extremely high significance level. In addition, the intersection of UF and UB was located between the critical lines, thereby identifying 1997 as the start of the abrupt change in temperature.

According to the trend analysis described above, the cumulative departure curve analysis and M–K mutation analysis based on temperature showed that during the 55-year research period, the temperature in Southern China increased continuously from 1976 and it increased abruptly after 1997.

### 3.1.2 Climatic variations before and after the abrupt change of temperature

The research period could be divided into two episodes with the year 1997 as the boundary: the first period (i.e., the period before significant temperature rise) from 1961 to 1996 and the second period (i.e., the period after significant temperature rise) from 1997 to 2015. In order to highlight the effects which result from obvious warming, a comparison of above factors between the two episodes and the trend of these factors in the two episodes are analyzed respectively. It shows that, during the period after significant temperature rise, most areas of SWC and the southern part of MLYZ have experienced a significant upward trend in temperature and downward trend in precipitation (Figs. 5 and 6). The difference in temperature during the period 1997 to 2015

and the period 1961 to 1996 (Fig. 7a) showed the temperature in the whole area as a positive value, demonstrating that the temperature of Southern China was clearly higher in the period after significant temperature rise than that in the period before significant temperature rise, indicating that Southern China have experienced the serious impacts of global warming after 1997. The difference of precipitation between the period before and after significant temperature rise was positive in most areas of SWC, including central and eastern Sichuan and Yunnan, most of Guizhou and Chongqing, and western Guangxi (see Fig. 7b), indicating that the precipitation in the period after 1997, namely the significant temperature rise period, was less than that of the period before the significant temperature rise.

3.2 Variations of drought disaster

3.2.1 Regional distribution of drought-affected agricultural areas

Agriculture has a very important role in the economy of Southern China, where the rice-growing, winter wheat-growing, and corn-growing areas comprise 81.2, 34.9, and 20.5% of the total area, respectively. During 1951 to 2014, there were significant differences in the average areas affected by drought each year (Fig. 8). In Sichuan Province, the average drought-affected area was the largest with 134.4×10^4 hm², which accounted for 17.4% of the total drought-affected area in Southern China. In
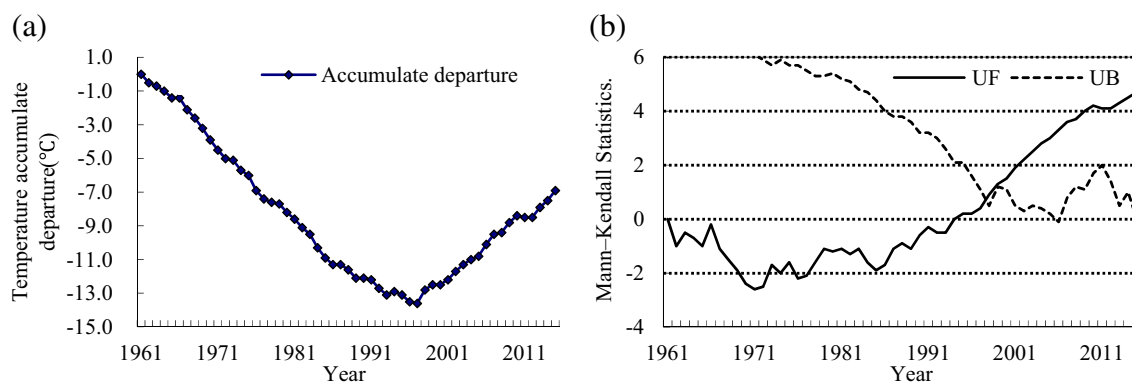
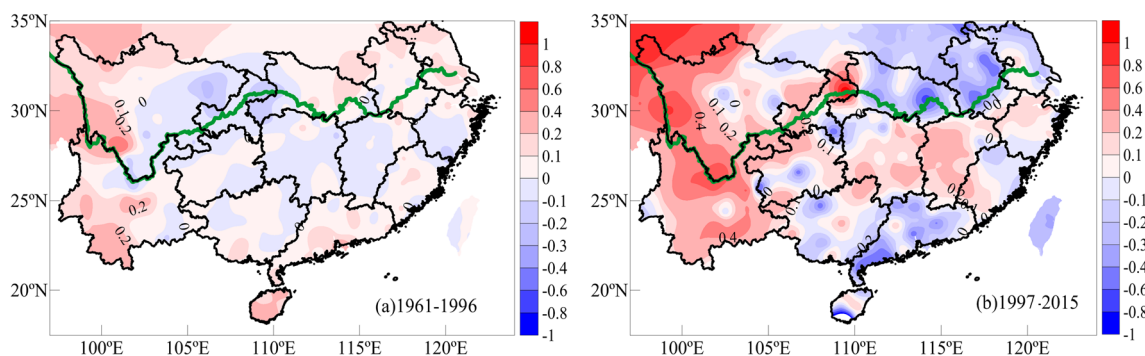**Fig. 4** Cumulative temperature departure curve (**a**) and M–K test results (**b**) for Southern China

Fig. 5 Trends of annual mean temperature during the period before (**a**) and after (**b**) 1997 in Southern China (unit: °C decade^{-1})

Anhui Province, the drought-affected area was 117.8×10^4 hm^2, which accounted for 15.2% of the total drought-affected area. In Hubei, Hunan, and Jiangsu, the drought-affected areas ranged from 83.9×10^4 to 108.0×10^4 hm^2, and the proportions affected ranged from 10 to 14%. In Yunnan, Guangxi, Guizhou, Chongqing, Jiangxi, and Guangdong, the drought-affected areas were between 45.0×10^4 and 60.6×10^4 hm^2, and they accounted for 6 to 8%. In Zhejiang, Fujian, and Hainan, the drought-affected areas were less than 26.6×10^4 hm^2, which comprised less than 5% of the total area. In Hainan Province, the annual average drought-affected area was the smallest with 10.7×10^4 hm^2, which accounted for 1.4% of the total.

3.2.2 Variations of drought-affected agricultural areas

During 1951 to 2014, the average annual drought-affected agricultural area in Southern China was 774.0×10^4 hm^2. In 1978, the drought-affected agricultural area was the largest at 1889.5×10^4 hm^2. In the last 64 years, the drought-affected area has increased with a linear trend of 28.02×10^4 hm^2/10 a, which was not significant (Fig. 9). This indicates that the drought-affected area changed slightly in Southern China as a whole.

When considering each sub-region, its regional difference is large (Fig. 10). In SWC, the drought-affected area increased significantly at a rate of 31.3×10^4 hm^2 per decade (Fig. 10a). And after 1997, with the increase of temperature and the decrease of precipitation, the area increased obviously by 64.7×10^4 hm^2. There is no obvious linear change in drought-affected area in SC

and MLYZ during 1951–2014; however, after 1997, due to the increase of precipitation in most parts of the region, the drought area decreases slightly than the early stage (Fig. 10b, c).

3.3 Risk characteristics of drought disasters

3.3.1 Risk assessment based on drought disasters in typical areas

SWC and SC were selected as typical areas for drought disaster risk assessment. According to Eq. (3), the distribution of the drought disaster risk was assessed in these typical areas using the analytic hierarchy process by considering the intensity and probability of drought disaster-causing factors, the social and physical exposure degree of risk (given the natural environmental conditions), the vulnerability to risk, the sensitivity of disaster-prone environments, and coping and resilience (disaster prevention and reduction) (Fig. 11).

In SWC and SC, the high drought disaster risk areas were located in central and eastern Yunnan Province, and eastern Sichuan Basin. The second high drought disaster risk areas were mainly in Yunnan Province, western Sichuan Plateau, the mountainous area of southwest Sichuan, and most of eastern Sichuan Basin. The medium drought disaster risk areas were in Yunnan-Guizhou Plateau, western Sichuan Plateau, and the mountainous area of southwest Sichuan, eastern Sichuan, central and western Guangxi, and southern Guangdong.
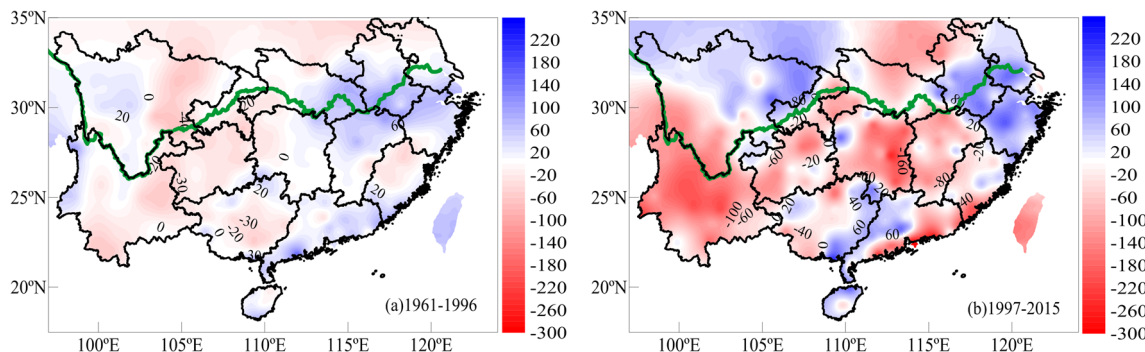

Fig. 6 Trends of annual precipitation during the period before (**a**) and after (**b**) 1997 in Southern China (unit: mm decade^{-1})
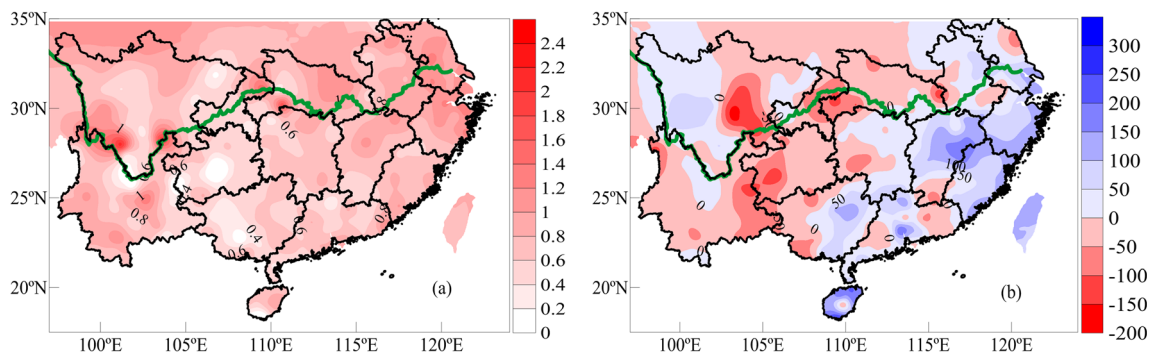
Fig. 7 Difference of average annual mean temperature (**a**) (unit: °C) and mean annual precipitation (**b**) (unit: mm) between periods of 1997–2015 and 1961–1996 in Southern China

3.3.2 Risk characteristics of drought disasters before and after the abrupt temperature change in the typical areas

In Southern China, the temperature increased abruptly around 1997. Figure 12 shows the characteristics of drought disaster risk before and after the abrupt temperature change in the typical areas. Before the abrupt temperature change, the highest drought disaster risk areas were mainly concentrated in central and eastern Yunnan Province, and the southern coast of Guangdong Province (Fig. 12a). After the abrupt temperature change, the highest drought disaster risk areas were mainly in eastern and northern Yunnan, and eastern Sichuan (Fig. 12b). The secondary highest drought disaster risk areas were mainly in Yunnan Province, the mountainous area in northern Sichuan, and southern Guangdong before the abrupt temperature change, but they expanded to Yunnan-Guizhou Plateau, eastern Sichuan, and central and western Guangxi after the abrupt temperature change.

Therefore, the secondary highest drought disaster risk areas expanded after the abrupt temperature change.

3.3.3 Probability distribution for the risk of severe drought

Based on the analysis of the variations in the drought-affected agricultural areas, there was a significant increasing trend in

SWC. After analyzing the probability of drought risk following the abrupt temperature change, we found that the high-risk areas for severe drought were mainly concentrated in SWC, including central and eastern Sichuan, central and eastern Yunnan, most of Guizhou, most of Chongqing, and western Guangxi. In these regions, the frequency and intensity of drought disasters and drought-affected areas increased, and the drought disaster risk also increased.

3.3.4 Prediction of future drought disasters

Results from BCC_ CSM1.1- RegCM4.0 simulations showed that in the future (2020–2050), the annual mean temperature in Southern China will increase under RCP4.5/RCP8.5 scenario by 0.22 °C/10a and 0.32 °C/10a, respectively. The annual precipitation will reduce especially in SC and Jiangnan region under RCP4.5 scenario. And under RCP8.5 scenario, it will reduce in SWC and SC by 40.7 mm/10a. The number of precipitation days (R 1 mm, Rday ≥ 1 mm) will decrease by about 3d/10a in the whole of Southern China under RCP4.5 and decrease by about 2d/10a in SWC and SC under RCP8.5. The maximum number of consecutive dry days (CDD, Rday < 1 mm) will increase in most of Southern China under RCP4.5 scenario and increase in parts of SWC and SC under

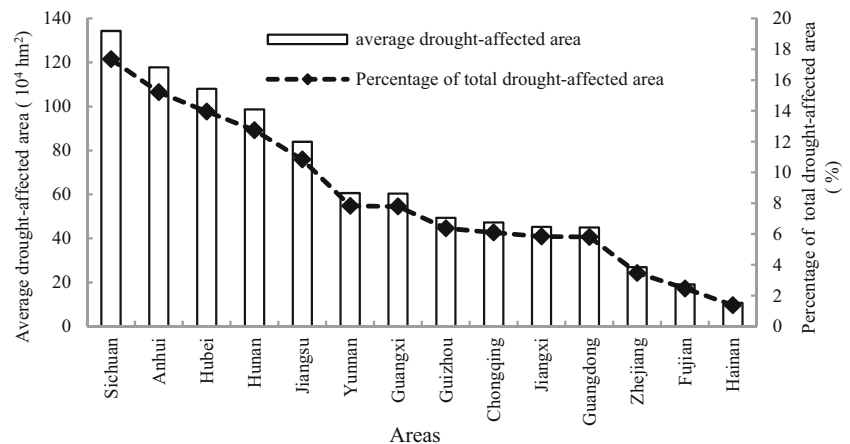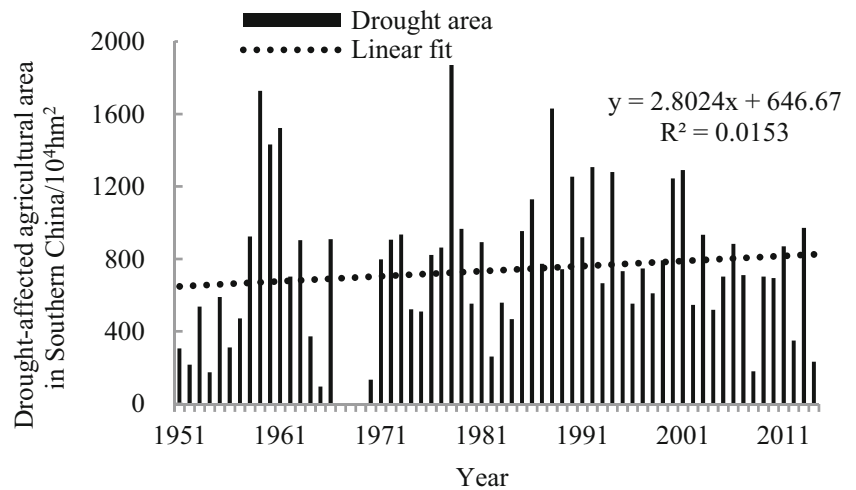**Fig. 8** Distribution of drought-affected areas in Southern China

Fig. 9 Variations in drought-affected agricultural area in Southern China

RCP8.5. On the whole, the occurrence of droughts may increase in Southern China in the future.

4 Drought disaster risk management in Southern China and prevention and control countermeasures

Drought disaster risk management can facilitate the design, implementation, and evaluation of suitable strategies, policies, and measures. Thus, the preparedness for disaster, disaster response, and recovery measures after a disaster can be enhanced by reducing and transferring the disaster risk. The aim is to improve human security, well-being, and quality of life,

as well as adaptability to change and sustainable development (Allen et al. 2012).

4.1 Conceptual model of drought disaster risk management strategy

Figure 13 shows a conceptual model of the drought risk management strategy for areas with different risk levels. (1) In the high risk region, where the risk is dominant by disaster-causing factor and influenced by disaster-prone environment, the conditions should mainly be improved by implementing weather modification to reduce hazard of disaster-causing factor, restoring the ecological environment to reduce the vulnerability of disaster-bearing body, adjusting and optimizing the crop cultivation structure and methods, strengthening the
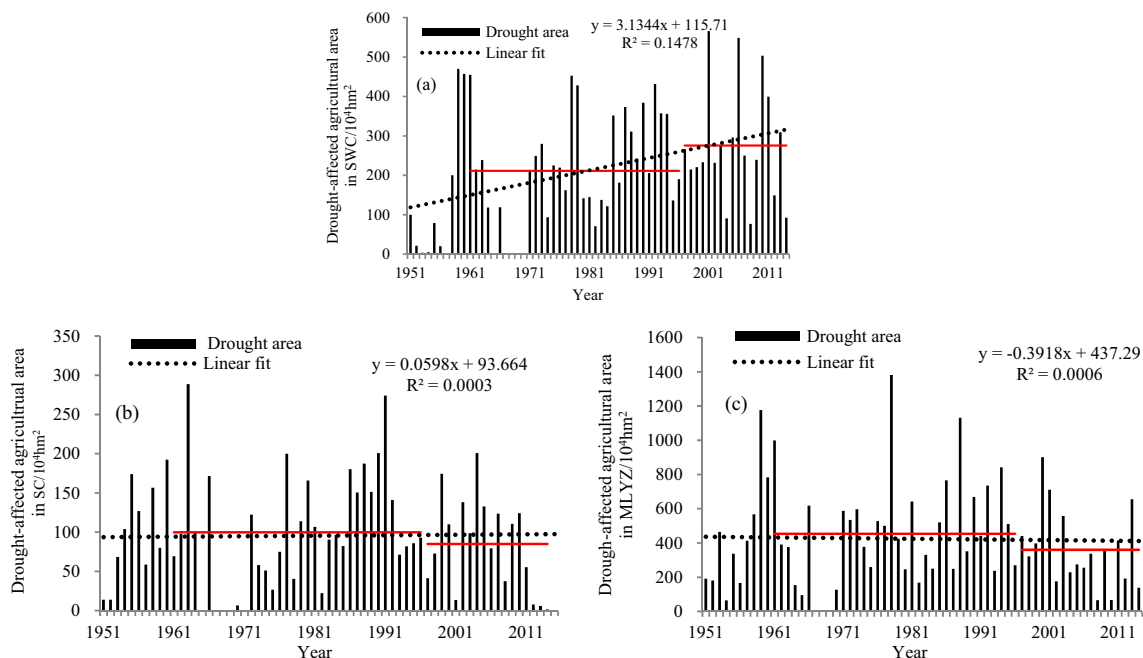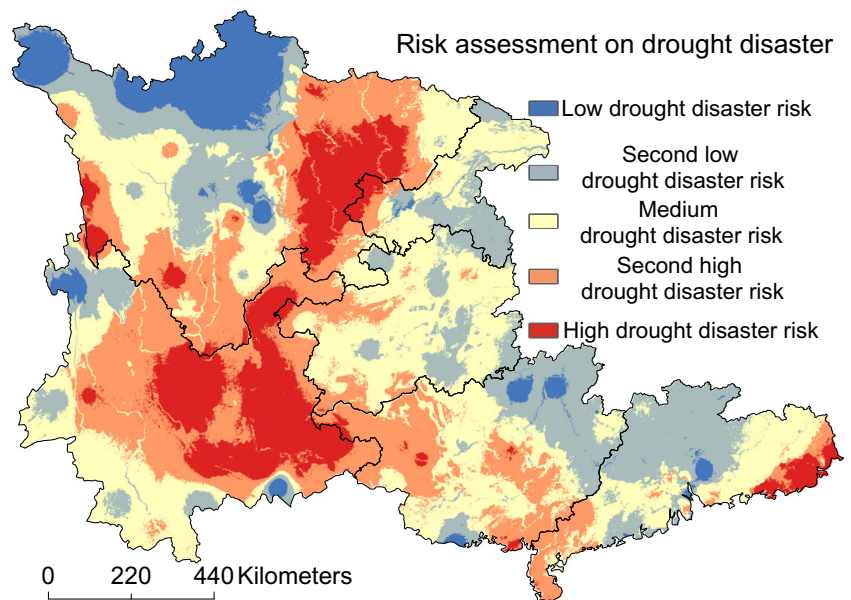

Fig. 10 Variations in drought-affected agricultural area in SWC (**a**), SC (**b**), and MLYZ (**c**)

Fig. 11 Assessment of the drought disaster risk in the typical areas

construction of water conservancy project and strengthening the system construction of drought risk early warning. (2) In the second high risk area, risk is dominant by disaster-causing factor, disaster-bearing body and disaster-prone environment all, so we must reduce the hazard of disaster-causing factor, the exposure and vulnerability of disaster-bearing body, and the sensitivity of disaster-prone environment, strengthening the construction of agricultural water resources utilization. Implementing industrial diversification and ecological protection strategy and improving non-engineering measures to improve the modernization, scientification and standardization of drought resistance. (3) In the medium and low risk area, the exposure and vulnerability of disaster-bearing body are the dominant factors in risk. We can take some countermeasures reducing the exposure and vulnerability of disaster-bearing body, increasing the drought disaster prevention and protection capabilities in the typical ecosystem, adjusting crop cultivation structure and the cropping system, strengthening the construction of water resources utilization and the planning

and infrastructure for disaster prevention and reduction, and building early warning system.

Figure 14 shows a conceptual model of the drought risk management strategy with respect to different risk control factors. (1) In the high risk region of disaster-causing factors, scientific measures are required where the main strategies aim to increase artificial precipitation, enhance the dew utilization efficiency, avoid highly dangerous periods (i.e., by staggering the exposure period and highly dangerous period), and reducing evaporation by plastic film mulching. (2) In regions with a high level of exposure to risk, the drought resistance mechanisms should be enhanced, where the main strategies include the development of drought-resistant plant varieties and increasing drought adaptability, the implementation of an industrial diversification strategy and reducing the vulnerability of the social economy, returning farmland to woodland and decreasing the degree of exposure to drought risk, and changing the crop-growing season to reduce the period of exposure to drought risk. (3) In highly sensitive drought-prone environments, the conditions should mainly be
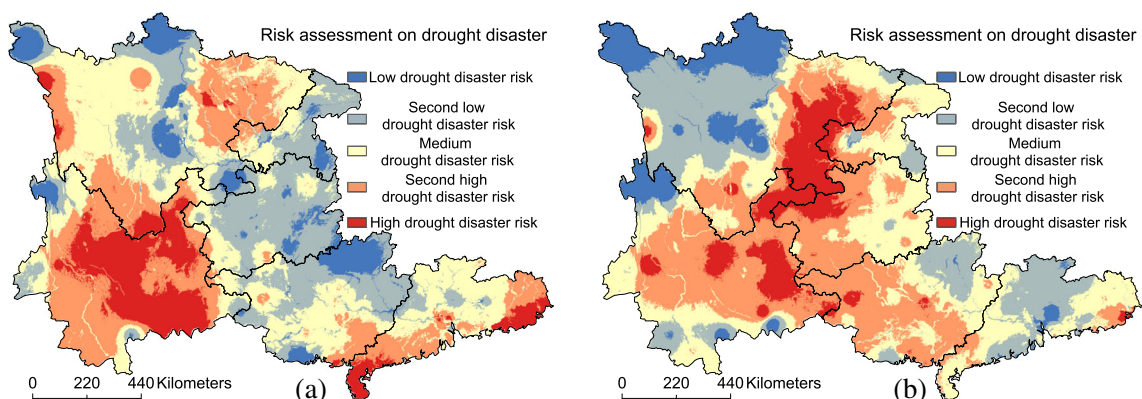

Fig. 12 Characteristics of drought disaster risk in the typical areas before (**a**) and after (**b**) 1997
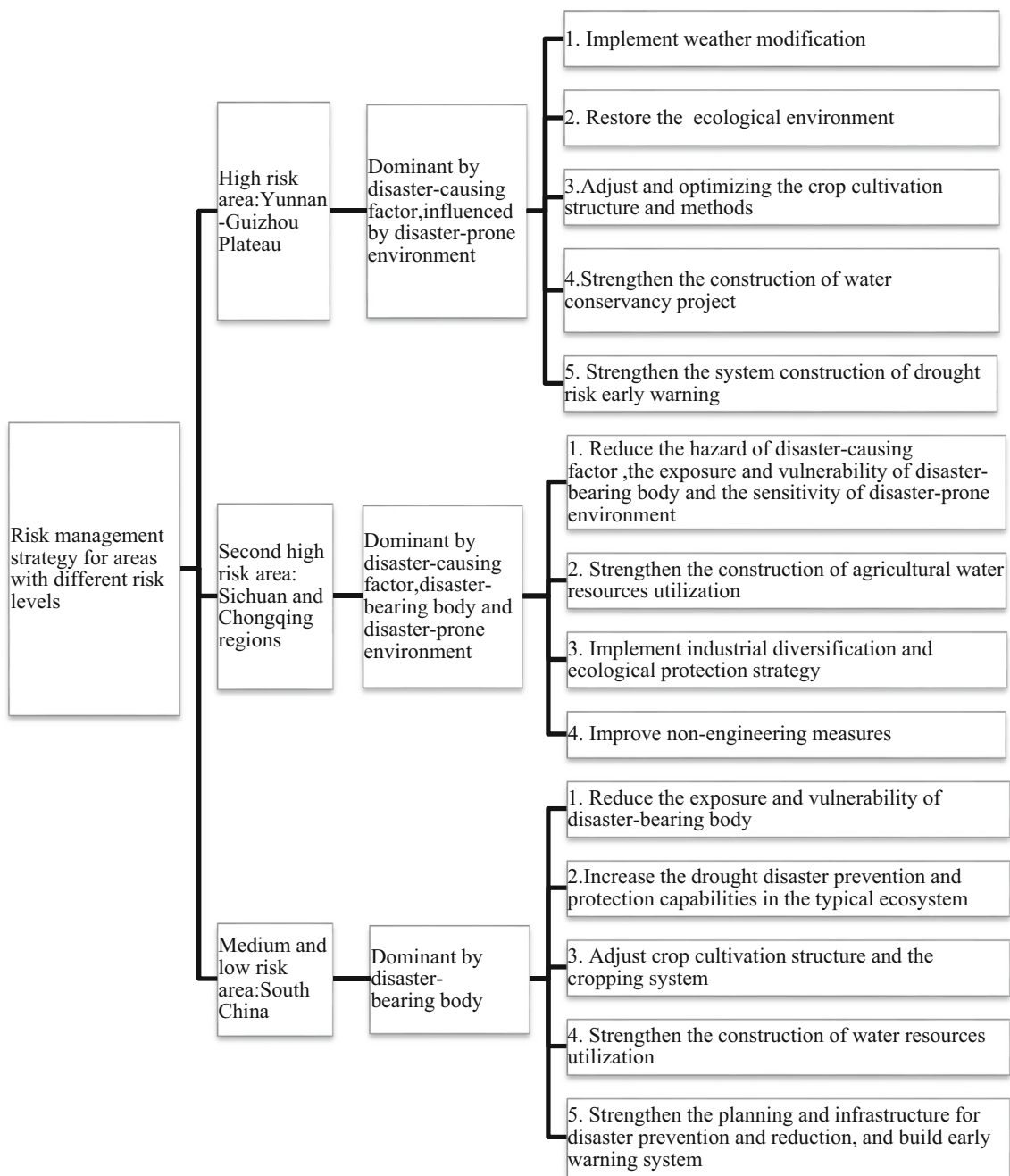
Fig. 13 Conceptual model of drought risk management strategy for areas with different risk levels

improved by enhancing the eco-environment, increasing the moisture content retention capacity, enhancing the hydrological conditions, increasing the guaranteed water resource capacity, promoting edaphic conditions, and increasing the soil moisture content. (4) In the regions with weak disaster prevention and reduction capacities, the drought resistance ability should be strengthened, where the main strategies include the development of techniques for drought disaster reduction, construction of anti-drought projects, increasing scientific knowledge of drought resistance among the public, enhancing drought monitoring and prediction, and increasing the risk management capacity.

Figure 15 shows a conceptual model of the drought disaster risk management strategy for different risk bearing body.

The following control strategies are recommended to address the drought disaster risk for agricultural areas: (1) meteorological monitoring, early warning, and response systems for drought disasters; (2) risk avoidance by using a planting pattern that can effectively avoid drought risk; (3) enhancing risk prevention and the control of drought disasters on farmland according to a diversified and scalable operation; (4) coping with risk by developing a technique for adapting to agricultural drought and establishing an agricultural drought disaster insurance policy system.

Fig. 14 Conceptual model of the drought risk management strategy for different risk control factors

The following control strategies are recommended to address the drought disaster risk for water sources: (1) establishing meteorological monitoring, early warning, and response systems for drought disasters, increasing the system construction of the engineering facility of emergency water resource; (2) establishing safe operating standards for water conservations projects and water supply systems, and regulating management and decision-making systems for water resources; and (3) constructing flood control, drought relief, and disaster reduction systems in high risk areas, and optimizing the efficiency of allocating water resources according to a market mechanism.

The following control strategies are recommended to address the drought disaster risk for the ecosystem: (1) establishing a risk control method for the natural ecosystem and an ecological compensation mechanism and improving the

drought disaster prevention and protection capacities in typical ecosystems and (2) implementing a pilot demonstration of regional ecology recovery and drought disaster prevention and control, as well as projects for ecological migration, tourism development, and ecological protection.

Figure 16 shows a conceptual model of the drought risk management strategy for different crops. (1) For rice, in the highest risk stage (seeding emergence) and the secondary highest risk stages(three-leaf to transplanting) of early-season rice, as well as the secondary highest risk stage(seeding emergence) of middle-season rice, we should increase the water supply. (2) For winter wheat, in the secondary highest drought risk stages, i.e., the jointing to booting stages, weeding and preserving soil moisture can effectively avoid drought risk .in the over-wintering stage, we can compact soil and preserve soil
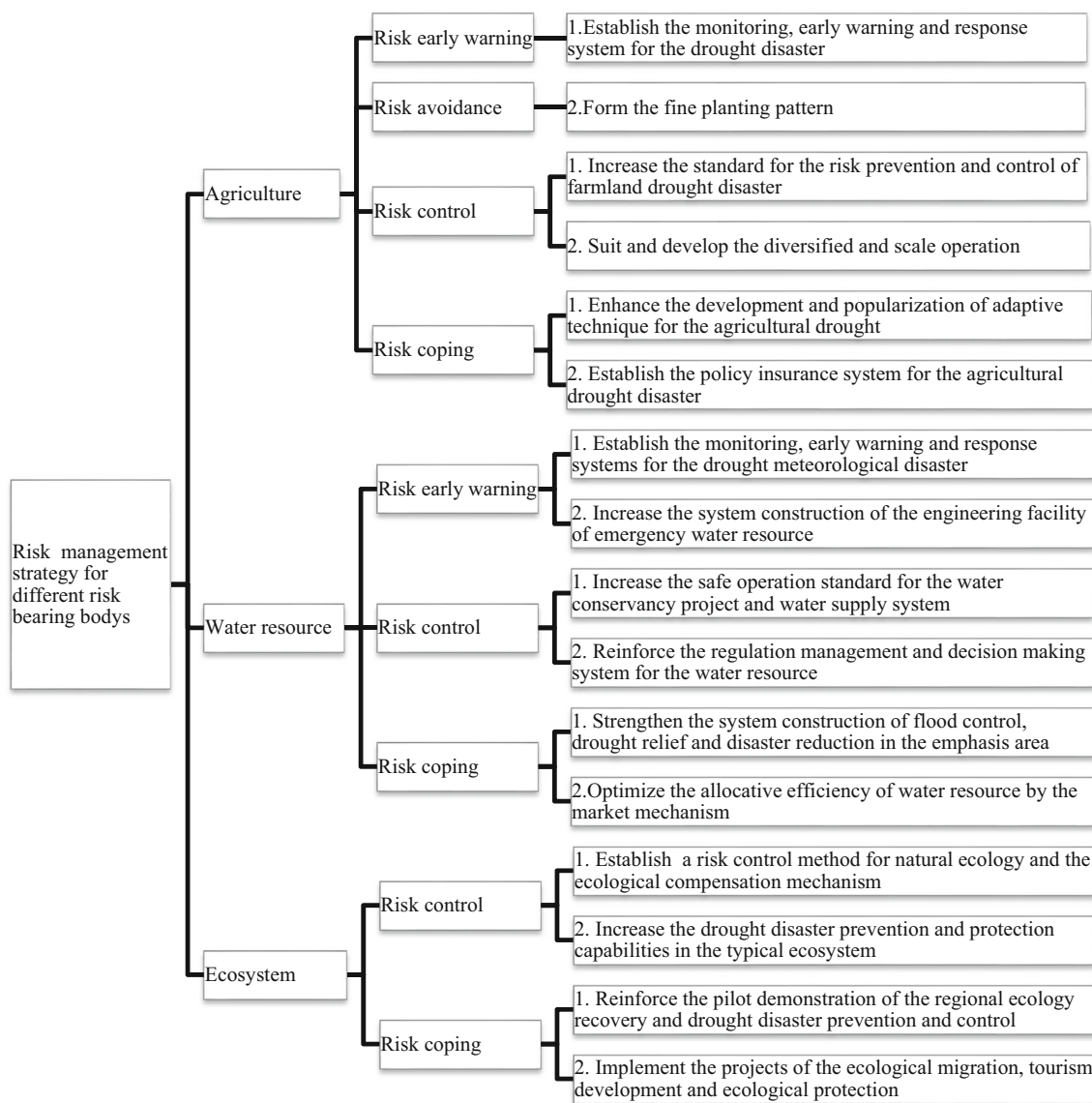
Fig. 15 Conceptual model of the drought risk management strategy for different risk bearing body

moisture, in the highest risk stage (reviving to standing) and the secondary highest drought risk stages(three-leaf to tillering), irrigation and topdressing should be done. (3) For spring corn, in the seeding emergence stage when the risk is highest, irrigation is an effective measure to protect the seedling. In the secondary highest risk stage (three-leaf to seven-leaf), countermeasures like weeding, scarification, and preserving soil moisture are recommended to address.

4.2 Technical countermeasures for drought disaster prevention and control

The following specific risk prevention and control countermeasures are proposed based on the drought disaster risk management strategy according to the drought disaster risk distribution characteristics in different regions.

4.2.1 Implementation of weather modifications and development of air water resources in high risk regions for drought disasters

The high-risk regions for drought disasters are those with low precipitation but also the regions with a high comprehensive loss ratio for agricultural drought, such as the Yunnan-Guizhou Plateau, which is located in the southwest water vapor channel. About 20% of cloud water resources in the air fall as precipitation and the other 80% flows out of the region. Thus, there is great potential for developing the air water resources and weather modifications may be important for affecting the drought disaster-causing factors. The air water resources can be developed by inducing artificial precipitation in dry periods in order to increase the water resource utilization
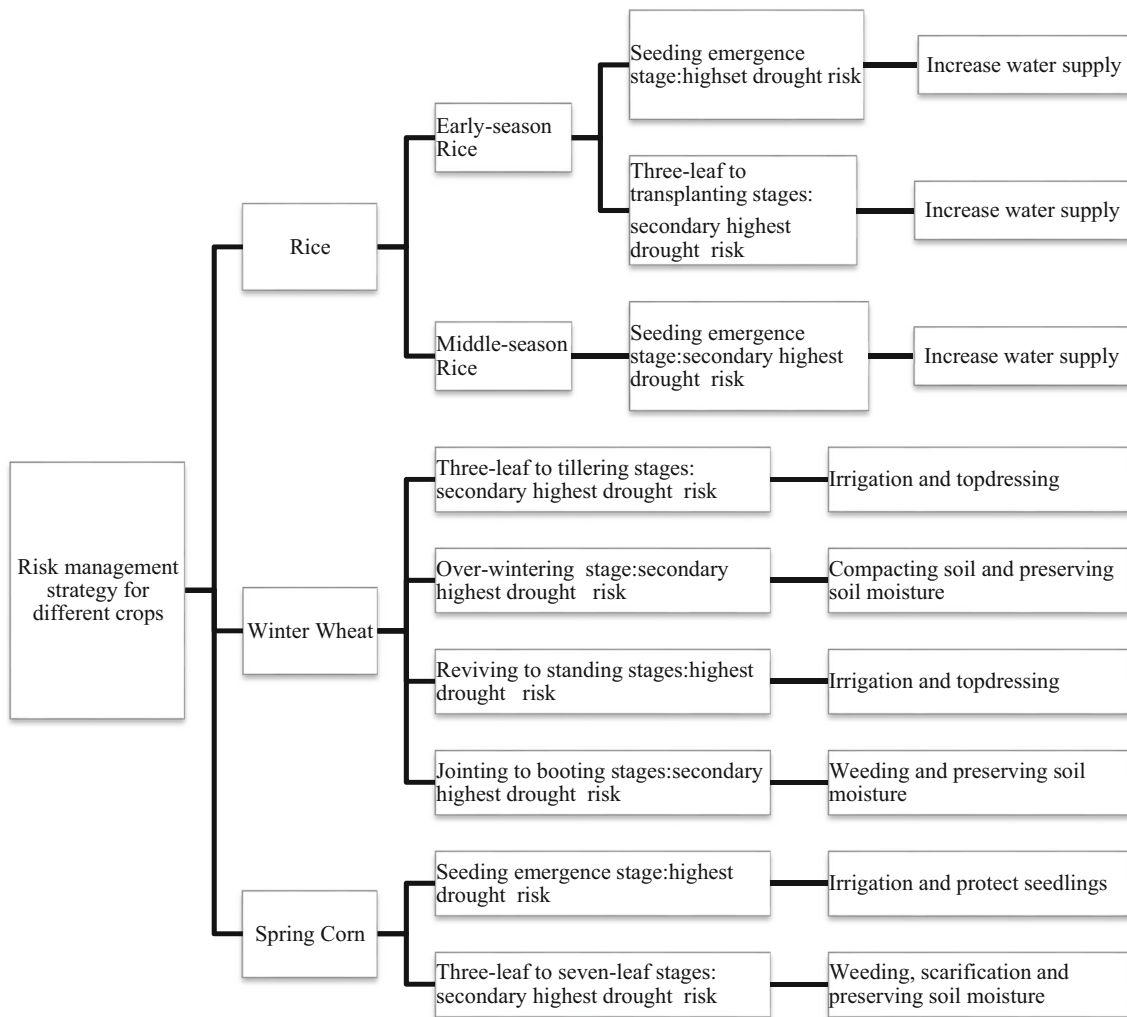
Fig. 16 Conceptual model of the drought risk management strategy for different crops

efficiency, alleviate droughts, and decrease the drought disaster risk.

4.2.2 Implementing eco-environmental modifications in vulnerable areas

The drought disaster risk and eco-environmental vulnerability are high in the Yunnan-Guizhou Plateau, most of Guangxi, and the middle and upper reaches of the Yangtze River. The drought disaster risk is related to the regional ecology and natural environment. The vulnerability to risk can be decreased by eco-environmental modifications. The eco-environment can be improved by conversion from cropland to forest (or grassland), combining agriculture and forestry, and developing a hybrid ecological system based on agriculture, forestry, and animal husbandry. Forest and water conservation projects can protect and develop the ecological environment to establish a balanced and stable ecosystem. Thus, improving the stress-resistance capacity and restoring the ecosystem can reduce the drought disaster risk.

4.2.3 Guaranteeing food security and implementing strategies to reduce the agricultural risk

Drought disasters increase the instability of food production, aggravate agro-meteorological disasters, and increase the frequency of diseases, pests, and weeds, thereby increasing the cost of farmland management, agriculture, and animal husbandry, and threatening food security. Thus, countermeasures are required to reduce the risk for agricultural production by establishing an early warning monitoring system, as well as response and disaster prevention methods in order to cope with climate change and climatic disasters, including disaster prevention and reduction planning, constructing appropriate infrastructure in agricultural fields, increasing protection against disaster by water conservation and irrigation engineering, and implementing an agricultural disaster policy insurance system. Demonstration areas for drought resistance and water logging prevention should be constructed in agricultural fields. The cultivation pattern, planting structure, and cropping systems should be optimized, as well as improving resource

management patterns for farmland, woodland, and grassland where greater adaptation must be explored. Training should be provided in adaptive techniques, including agricultural water-saving methods, drought resistance, and water logging prevention, stress resistance, and conservation tillage.

4.2.4 Rational utilization of water resources to address the uneven spatial and temporal distribution of water resources

The drought disaster risks for water resources mainly include aggravating the uneven spatial and temporal distribution of water resources, increasing the discrepancy between the supply and demand of regional water resources, i.e., increased water requirements and reduced resources, as well as increased hydrologic drought, extreme precipitation, and urban flood risks, and threats to water security and the water environment. To address the risk for water resources, a monitoring and emergency management system is required to cope with extreme hydrologic and climate events, as well as improving the safe operation of water conservations projects and water supply systems by enhancing flood control, drought relief, and disaster reduction systems for important cities, rivers, lakes, reservoirs, flood protection zones, and severe drought regions. The efficient allocation of water resources should be optimized according to a market mechanism, and water rights reform and paid use systems for water resources must be promoted. In addition, the development and application of water-saving technology and water-saving products, including rain-flood utilization, circulating water, seawater desalination, and saline-alkaline water, should be encouraged to cope with future shortages of water resources.

4.2.5 Decreasing the effects of drought disasters on territorial resources based on their sustainable utilization

Drought disasters mainly affect territorial resources by affecting the quality and sustainable utilization of land resources, increasing the costs of land governance and protection, aggravating soil-water protection stress, geological safety, and environmental protection, and triggering or increasing the risk of geological disaster, such as debris flows, surface collapses, landslides, and mountain collapses. Thus, it is necessary to improve land planning by focusing on assessments of the environmental resource-bearing capacity, performing risk assessments regarding meteorological and geological disasters for major projects, and enhancing the exploitation, utilization, supervision, and protection of land resources. Engineering measures and ecological restoration measures should be applied to reduce water and soil losses and geological disaster, as well as protecting the geological environment in mines and restoration control projects. Monitoring of the geological environment must be increased and the adverse effects of abrupt geological events caused by the floods and drought on the social economy need to be reduced.

5 Discussion and conclusions

During 1961–2015, the precipitation fluctuated greatly in Southern China but the linear trend was not significant. However, the decrease in the average precipitation was obvious in Southern China during the early twenty-first century. Moreover, the inter-annual oscillation amplitude of the average precipitation increased. In the 55-year period considered in this study, the temperature exhibited a significant increasing trend in the study area. In Southern China, the average increase in the surface temperature was higher than the overall global increase. Before the 1980s, the average temperatures exhibited negative departures in Southern China. Subsequently, the departures were ≥ 0 °C, and the coefficient of variation and the oscillation amplitude of the temperature also increased. In the 55-year research period, the temperature increased gradually from 1976, but then increased abruptly after 1997. In Sichuan Province, the average drought-affected area was the largest, where it accounted for 17.4% of the total drought-affected area in Southern China. In Anhui Province, the drought-affected area increased significantly. The high-risk areas for severe drought were concentrated mainly in SWC. As the temperature increased, the frequency and intensity of drought disasters and the drought-affected areas increased, and the drought disaster risk also increased. After the abrupt change in temperature, the secondary highest drought disaster risk areas expanded greatly.

In the future (2020–2050), the annual mean temperature in Southern China will increase. The annual precipitation will reduce. The number of precipitation days will decrease by about 2~3d/10a. And the maximum numbers of consecutive dry days will increase. So, the occurrence of droughts may increase in Southern China. Analysis of future climate changes in Southern China was based on results from BCC_CSM1.1-RegCM4.0 simulations. BCC_ CSM1.1 - RegCM4.0 had a good performance in reproducing the temperature and precipitation in most of Southern China for the present day period, but uncertainties still exist in SWC because of poor observations and discrepancies between simulations and observations (Xu and Xu 2012; Gao et al. 2013). In addition, although the prediction of future climate changes in Southern China was consistent with other previous CMIP5-based studies. The magnitude and regional characteristics are different (Wang and Chen 2013; Zhang et al. 2015b; Zhang et al. 2017). Uncertainty of future assessments exists because of the incomplete and uncertainty of the model. Hence, further work should be conducted to improve the capability of this model to simulate climate through improvements in model resolution and the representation of physical processes. And the multi-model ensemble method adopted in CMIP5 models should also be utilized to verify the above results.

The proposed conceptual model of drought disaster risk provides a better understanding of the causes of drought

disasters by illustrating the development of drought disaster risks, as well as reflecting the variability and the characteristics of this dynamic process. Drought disasters have social and natural effects. Thus, drought disasters should be considered from the perspectives of the natural and social sciences. Drought disaster risk assessments must include deep considerations of the arid climate laws as well as research into eco-environment and socioeconomic systems. The theoretical basis of drought risk assessments also needs to integrate meteorology and other sciences. Based on the natural laws that underlie the occurrence and development of droughts, drought disaster risk management should reflect the principles of drought risk sharing and economic optimization (Zhang et al. 2014).

In the context of climate warming, the frequency of drought disasters has increased in Southern China, where the intensity and the areas affected have also increased, and thus the comprehensive loss ratio for agricultural drought disaster has increased. However, our systematic understanding of the effects of drought disasters on agriculture, water resources, and ecosystems, and the corresponding mechanisms involved are not sufficient at present. Thus, it is important to study the scientific assessment of drought disaster risks and suitable preventative countermeasure. Risk assessments can be performed to determine specific risks and the relevant risk level. In the present study, based on analyses of the hazards associated with drought disaster-causing factors, the risk exposure degree (vulnerability), and the sensitivity of disaster-probe environments (Yang et al. 2010; Shi 2002; Zhang et al. 2012a, b), we assessed the drought disaster risks in Southern China and proposed suitable countermeasures, so passive disaster prevention can be converted into active defense. This study provides a scientific basis for drought disaster management and defense.

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