Research Article

Cumulative Effect of Precipitation Deficit Preceding Severe Droughts in Southwestern and Southern China

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Timely and accurate monitoring of droughts is important for implementing an effective response and for minimizing economic losses. In this paper, the duration and amount of deficit in precipitation before every severe drought were analyzed for 124 meteorological stations based on the weather data from 1961 to 2012. The results showed that deficit in precipitation over a period as short as three months or even shorter could lead to severe drought and the cumulative timescales of precipitation deficit in southwestern China were longer than those in southern China. The distribution of the critical amount of precipitation deficit showed a clear regional difference. Deficits in the western parts of southwestern China and parts of southern China are above 60%, or even above 80%, higher than the other area ranging between 40% and 60%. On the whole, the critical amount of the deficit preceding severe droughts for the humid southwestern and southern China was lower than that for the semiarid and semihumid areas. The results offer a sound basis for monitoring and forecasting droughts in southern and southwestern China and for issuing early warnings.

1. Introduction

Drought is the world's costliest stochastic natural disaster affecting more people than any other natural disaster [1] and has been more frequent in recent years over increasingly larger areas [2]. Whereas severe and frequent droughts were common in northwestern and northern China in the past, southwestern and southern China that used to have abundant precipitation have now begun to experience severe droughts, resulting in enormous economic losses [3–15].

Timely and accurate monitoring of droughts is important for implementing an effective response and for minimizing economic losses [16]. However, previous studies on drought focused mainly on “postdisaster analysis,” which is analysis of regional characteristics [3–15] or causes [17–22] of droughts. Forecasting and early warnings of a drought have always been the weak links in drought research. Research on critical factors that lead to droughts and characteristic patterns of weather data that normally precede a drought and the critical values of those factors linked to droughts has been

somewhat limited, with adverse impacts on the monitoring, early warnings, and risk assessments of droughts.

Drought is essentially a shortage of water caused by an imbalance in the supply of and the demand for water, usually triggered by a severe and persistent deficit in precipitation [23, 24]. However, drought is a slow process of accumulation of such deficit, and the severity of drought at a given moment is related not only to the current precipitation but also to the cumulative effect of earlier deficit in precipitation. What is the specific relationship between the duration and the amount of precipitation deficit and the severity of drought? What is the minimum duration of precipitation deficit that may lead to drought in southwestern and southern China? Reliable answers to these questions are a prerequisite to accurate monitoring, early warning, and risk assessment of droughts. Differences in temperature, humidity, and evapotranspiration across regions mean that the same degree of precipitation deficit may result in droughts of varying severity in different regions. In semiarid and semihumid regions, for example, a precipitation deficit of 80%–95% in a month or of 70%–80%

over three months can lead to severe drought, and a value greater than 95% in a month or 80% over three months can lead to extreme drought [25]. In Huaihe river basin, which is at the meeting point of semihumid and humid areas, droughts are severe if precipitation is limited to only 60%–70% of the average and extreme if the deficit exceeds 40% [26]. Among a few such studies on the critical values of precipitation deficit that can result in drought in southern humid areas is one by Huang et al. [27], who pointed out that, in most regions in southern China, severe droughts are linked to a 40% deficit in precipitation over a year and about 60%–80% deficit over a quarter. Fan et al. [28] maintain that, in Zhejiang province, a seasonal precipitation deficit of 50% would result in a severe drought. These results show the regional differences in critical values of drought-causing factors. Therefore, to carry out regional monitoring, forecasting, early warning, and risk assessment of droughts objectively and accurately, it is necessary to identify the characteristics of the occurrence and development of local droughts and choose objective criteria for judging the severity of droughts based on local conditions.

Based on the above analysis, those areas in southwestern and southern China that had faced severe or extreme droughts—as judged by the K drought index—in recent years were selected as research areas. By using weather data from 124 meteorological stations in the selected areas, the following features and values were determined: (1) the cumulative timescales of the precipitation deficit that preceded a severe drought at each station; (2) the amount of deficit (as a negative percentage of precipitation anomaly) that preceded a severe drought at each station. By comparing regional differences in the above features and values, their cumulative effect on droughts was estimated to provide a scientific basis for regional drought forecasting, for early warning, and for preventing such disasters or at least mitigating their impact.

2. Data and Methods

2.1. Study Area and Data. The study areas in southwestern (refer to Sichuan, Chongqing, Yunnan, and Guizhou provinces) and southern China (refer to Guangxi and Guangdong provinces) comprise 124 meteorological stations. Nearly all stations experience a subtropical climate; however, north-western Sichuan and the northernmost part of Yunnan are in the plateau climate zone and the southern parts of Yunnan and Guangdong provinces experience a tropical climate. The elevation ranges from below 400 m in the southeast to more than 3000 m in the northwest (Figure 1).

For each station, data spanning the years 1961–2012 were collected for a number of variables including monthly mean temperature, maximum temperature, minimum temperature, precipitation, sunshine hours, average wind speed, and relative humidity. All the data were obtained from the National Meteorological Information Center and meet the stipulated criteria for quality control.

2.2. Methods. The degree of drought severity is expressed with K drought index which has been extensively used in

FIGURE 1: The location of southwestern and southern areas in China, the spatial distribution of elevation (unit: m), and 124 meteorological stations (dot) in the study area.

southwestern and southern China [29], and Wu et al. [30] showed that the index is a reliable measure of agricultural and hydrological droughts.

The K drought index is defined [31] as follows:

$$K_{i,j} = \frac{R'_{i,j}}{E'_{i,j}}, \quad (1)$$

where $K_{i,j}$ is the K drought index and $R'_{i,j}$ and $E'_{i,j}$ are the relative variability rate of precipitation and reference evapotranspiration, respectively, over the stipulated period, i being the year number and j being the number of the meteorological station.

$R'_{i,j}$ is given by the following equation:

$$R'_{i,j} = \frac{R_{i,j}}{R_{pj}}, \quad (2)$$

where $R_{i,j}$ is the precipitation over the stipulated period and R_{pj} is the latest 30-year average of precipitation (the normal value) over the stipulated period.

$E'_{i,j}$ is given by the following equation:

$$E'_{i,j} = \frac{E_{i,j}}{E_{pj}}, \quad (3)$$

where $E_{i,j}$ is the reference evapotranspiration for the stipulated period and E_{pj} is the latest 30-year average of evapotranspiration (the normal value) over the stipulated period. The reference evapotranspiration was calculated using the

Penman-Monteith equation recommended by the FAO in 1998 [32]. The equation is defined as

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(900/(T + 273))U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}, \quad (4)$$

where ET_0 is the reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$), G is the soil heat flux density ($\text{MJ m}^{-2} \text{day}^{-1}$), T is the mean daily air temperature at 2 m height ($^{\circ}\text{C}$), U_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $e_s - e_a$ is the saturation vapour pressure deficit (kPa), Δ is the slope of saturation vapour pressure curve at air temperature T ($\text{kPa } ^{\circ}\text{C}^{-1}$), and γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

Following the approach proposed by Svoboda et al. [33], each drought was assigned a level from 1 to 5, depending on the severity of the drought (as shown by the K index) according to the percentile method (Table 1). Each category thus indicates the probability (percentile) that a drought of that severity will occur in any given year from 1961 to 2012.

The methods for calculating the cumulative timescales of precipitation deficit and the critical amounts of the cumulative precipitation deficit for each station are as follows. First, the severity of drought at each station is determined according to the monthly K drought index. If the severity of drought is severe or extreme, the drought process is regarded as severe drought. The month in which the drought is rated as above severe (category ≥ 4) for the first time is regarded as the starting month for a severe drought. Second, the cumulative months of negative precipitation anomaly before the occurrence of each severe drought at each station are counted. Additionally, the percentage of severe droughts caused by different durations (number of consecutive months) of precipitation deficit is calculated, and the cumulative timescales of precipitation deficit at each station are ranked in descending order of the above percentage and called the first, the second, the third, the fourth, and so forth, cumulative timescales of precipitation deficit. Third, the precipitation deficit preceding each drought is obtained and paired with the different cumulative timescales. The deficit amounts are divided into four classes in increments of 20% and the occurring frequency of deficit in each interval is counted. Finally, the deficit at each cumulative timescale for each station is ranked in decreasing order of the above frequency and called the first, the second, the third, the fourth, and so forth, precipitation deficit under each timescale.

3. Results and Analysis

3.1. Suitability of the K Index for Monitoring Droughts. The K index has proved its validity as a measure of the severity of drought in the study area [29]. This section chooses the severe drought from the autumn of 2009 to the spring of 2010 and the validity of the K index is further attested by examining the correspondence between the K index and the actual situation.

TABLE 1: Categories of the severity of drought as indicated by the K index.

Category	Degree of severity	Percentile chance (%)
1	No drought	>30
2	Incipient	15 to ≤ 30
3	Moderate	5 to ≤ 15
4	Severe	2 to ≤ 5
5	Extreme	≤ 2

As ascertained from the related literatures [15, 20, 34–37], droughts occurred mainly in the Yunnan and Guizhou Plateau area and moderate to severe droughts occurred in eastern Yunnan, western Guangxi, most parts of Guizhou, and eastern and northern Guangdong in September 2009. In October 2009, moderate droughts occurred in most parts of southern China and Yunnan and in southern parts of Guizhou; severe droughts occurred in the northern parts of Guangdong, western parts of Guangxi, and southeastern parts of Yunnan. In November 2009, the northern and eastern parts of Yunnan, southern parts of Sichuan, and western parts of Guizhou and Guangxi experienced severe droughts. In December 2009, most parts of Yunnan, southwestern parts of Guizhou, western parts of Guangxi, and southern parts of Sichuan experienced moderate to severe droughts. In January 2010, the drought in Guangxi was relieved, but the northern parts of Yunnan, southern parts of Sichuan, and western parts of Guizhou suffered severe droughts. In February 2010, Yunnan, Guizhou, Guangxi, and southern parts of Sichuan experienced a drought of more than moderate severity. Meanwhile, the droughts in central and northern parts of Yunnan, most parts of Guizhou, and southern Sichuan were moderate and even severe locally. In March 2010, droughts continued to develop. Eastern parts of Yunnan, northwestern parts of Guangxi, southwestern parts of Guangdong, southern parts of Sichuan, and southwestern parts of Guizhou faced severe droughts and, in some pockets, extreme droughts. In April 2010, multiple spells of precipitation were received in the southwestern drought areas, which mitigated the drought. However, moderate droughts were experienced in Yunnan, Guizhou, and northwestern Guangxi.

The results from monthly monitoring of the K index are shown in Figure 2: the locations and the severity as assessed by the index K closely match the actual condition. The index accurately reflects not only the severity of droughts but also their occurrence, development, mitigation, and relief. For example, in January 2010, Guangxi received 1.8 times the normal precipitation, thus bringing relief to the region. Therefore, the K index can be used to describe the drought situation in the study area accurately.

3.2. Cumulative Timescales of Precipitation Deficit. Figure 3 shows the frequency distribution of cumulative months of precipitation deficit preceding severe droughts: most were due to short-term (seasonal scale) deficits in precipitation, about half of the droughts being due to only a month's deficit. A deficit of 2–3 months accounted for 30% of the droughts and that caused by deficit over one season is less than 20%.

FIGURE 2: Distribution of droughts of varying severity as judged by the K index (Sept. 2009 to Apr. 2010).

FIGURE 3: Frequency distribution of cumulative timescales.

Figure 4 shows the distribution of the first four cumulative timescales at each meteorological station and also the percentage of droughts accounted for by each timescale. It

can be seen that the first timescale of precipitation deficit preceding severe droughts at each station was mainly 1 month. In most parts of south China, Yunnan and Chongqing, and the northeast part of Guizhou, droughts caused by the precipitation deficit at this timescale account for more than 50% of total droughts. That is, over half of the serious droughts in these areas were due to only a month's deficit in precipitation. In the rest of the study area, 30%–50% of the droughts were due to a deficit at a monthly scale (Figure 4(a)).

The second timescale was basically 2 months and accounts for 20%–30% of the total in most part of Sichuan, the western and southeast parts of Guizhou, and the western part of Guangxi and accounts for 10%–20% in the other areas (Figure 4(b)).

The third timescale was mainly 3 months, which accounts for 10%–20% of severe droughts (Figure 4(c)).

The fourth timescale was 4–6 months (Figure 4(d)). 10%–20% of droughts in West Sichuan Plateau and northern Yunnan are caused by precipitation deficits on this timescale.

FIGURE 4: The first 4 cumulative timescales of precipitation deficit (red markers map, unit: month: (a) the first; (b) the second; (c) the third; (d) the fourth) and the proportion of droughts (blank map, unit: %) due to the deficits of each timescale.

It can be seen that those severe droughts due to extended periods (4–6 months or longer) of precipitation deficit were fewer: most of them are accounted for by deficits lasting up to 3 months. However, droughts due to extended periods of deficit are usually rare, perhaps once in several decades or a century. For example, the severe summer drought in Sichuan and Chongqing in 2006 was preceded by a deficit of 4–5 months in most of the areas (Figure 5). Southwestern China experienced its most severe and sustained drought on record from the autumn of 2009 to the spring of 2010. The deficit lasted over 4–6 months and even longer in some areas (Figure 6), and the longer the duration, the greater the damage [20, 22, 38].

The cumulative timescales of precipitation deficit that preceded severe droughts in southwestern China were longer than those in southern China. Severe droughts in southern China were caused mainly by 1-month deficits, whereas in most parts of Sichuan and northern Yunnan, besides the droughts due to 1-month deficit, those due to deficits longer than 2 months are more frequent than other areas.

3.3. Critical Amount of Precipitation Deficit. The analysis in Section 3.2 shows that the duration of precipitation deficit that preceded severe droughts was typically 1–3 months. The

next question is this: On that timescale, what was the amount of deficit that led to severe droughts? The following analysis is therefore confined mainly to the timescale of (a) 1 month and (b) 2–3 months.

3.3.1. Amount of Precipitation Deficit on a Timescale of 1 Month. Figure 7 shows the first four precipitation deficits (as a percentage of deviation from the normal average value for a given station) at one-month timescales of each station and the proportion of droughts (as a percentage of the total number of severe droughts) due to varying degrees of deficit. In Sichuan, Yunnan, and most parts of Guangdong, the more severe droughts occurred when the deficit was more than 80%. And, in most parts of Chongqing, Guizhou, and Guangxi, the deficit that led to severe droughts was smaller: a 60% deficit—or even 40% in some small pockets. In western parts of southwestern China, about 70% of the severe droughts were caused by monthly deficits in precipitation exceeding 80%; in other areas, 30%–60% of the severe droughts were caused by deficits of 40%–80%. The distribution seen in Figure 7(b) is complementary to that in Figure 7(a): in most parts, 20%–40% of the severe droughts were linked to monthly deficits greater than 60%, whereas, in the West Sichuan Plateau, Chongqing, Guizhou, and northeastern Guangxi,

FIGURE 5: Cumulative months of negative precipitation accumulation: June–August 2006.

FIGURE 6: Cumulative months of negative precipitation accumulation: October 2009–March 2010.

a much smaller deficit (20%–40%) accounted for the same proportion of droughts. The remaining panels of Figure 7 (Figures 7(c) and 7(d)) show that, in eastern Guangxi, 20% of the severe droughts were due to deficits of 80%–100%; in most parts of Yunnan and Guangdong and in central and western Guangxi, about 10% of the severe droughts were due to deficits of 20%–60%; in most parts of Guizhou, about 20% of the droughts were due to a deficit of 20%–60% and about 10% were due to a deficit of more than 60%.

As the droughts caused by precipitation deficits around 40%–100% accounted for about 90% of the total number of severe droughts, each of the amounts of deficit was given a weighting equivalent to the percentage of the total number of droughts due to that category of deficit (Figure 8). It can be seen from Figure 8 that except for some parts of Chongqing, Guizhou, and north-central Guangxi, the monthly precipitation anomaly percentage of 80%–100% covered most of the study area—in other words, when the precipitation deficit reaches 80%, a severe drought is most likely to occur, a pattern consistent with the situation in semihumid and semiarid areas [25]. However, the critical value of precipitation deficit is smaller for southern China

and the eastern parts of southwestern China; in these areas, the critical value is 60%–80% or even as low as 40% in some small pockets.

3.3.2. Cumulative Deficit in the Amount of Precipitation on a Timescale of 2–3 Months. Figure 9 is similar to Figure 8 except that it shows the distribution of precipitation deficit on a timescale of 2 months (Figure 9(a)) and 3 months (Figure 9(b)). It can be seen that the critical value of precipitation deficit lasting for 2 months is lower than that when the deficit lasts for only 1 month. In the western parts of southwestern China and the coastal areas of southern China, the critical value is 60%–80%, whereas for other areas it is 40%–60%. When the deficit lasts for 3 months (Figure 9(b)), the critical amount was about 40%–60% in most of the areas—far lower than the critical value of 70%–80% for the semihumid and semiarid areas [25]. This indicates that the critical threshold of precipitation deficit leading to severe droughts is lower in southwestern and southern China. In other words, the same amount of deficit that led to only mild droughts in the semihumid and semiarid areas caused severe droughts in southwestern and southern China. Moreover, a precipitation deficit lasting for 2 or 3 months accounted for 20%–30% of the severe droughts in north-central Sichuan but only for 10%–20% of them in the remaining areas. This further indicates that the cumulative timescales leading to a severe drought in some parts of Sichuan were longer than that in other areas, and those parts are therefore more likely than other areas to suffer severe droughts caused by long time of negative precipitation accumulation.

3.4. Regional Differences in the Critical Threshold of Precipitation Deficit. To examine regional differences in the critical threshold of precipitation deficit in greater detail, the research area was divided into three subareas, namely, the western parts of southwestern China (Yunnan and Sichuan), the eastern parts of southwestern China (Guizhou and Chongqing), and southern China. The division was based on the characteristics of the spatial distribution at different timescales and under varying amounts of the deficit discussed above. The relationship between the cumulative timescales and the cumulative amount of precipitation deficit was examined by plotting their respective values for each of the three subareas. Another area—the semiarid and semihumid areas—was also introduced in the same graph (Figure 10). The critical value for drought in the eastern parts of southwestern China was the lowest and matched the value for the humid areas, whereas the critical value for the western parts of southwestern China was the highest. The critical value for southern China fell between the above extremes. The differences in the cumulative amounts of the deficit for each area were the largest on the timescale of 1 month or 2 months. In the eastern parts of southwestern China, severe droughts followed a precipitation deficit of about 60% for 1 month and of about 40% for 2 months, whereas, for the western parts of southwestern China, the corresponding values were 80% and 50%. As the timescale was extended, the critical value of precipitation deficit decreased and so did the regional differences. The critical value for each area

FIGURE 7: The first 4 precipitation deficits (colored dot, unit: %: (a) the first; (b) the second; (c) the third; (d) the fourth) under one-month timescale and the proportion of droughts (blank map, unit: %) due to varying degrees of deficit.

on a timescale of more than 3 months is basically 40%. The critical value for humid areas was the lowest irrespective of the timescale: in humid areas, severe droughts occurred following a smaller precipitation deficit, which is consistent with the research results of Huang et al. [27] and Fan et al. [28]. The average critical values of precipitation deficit in the transitional zone between semiarid and semihumid areas in the western parts of southwestern China are smaller than those in the semihumid and semiarid areas on the timescale of a month or several months (a season). However, spatial distribution of the critical values shows that the critical values for more than half the meteorological stations were close to those in the semihumid and semiarid areas.

4. Discussion and Conclusion

(1) Most of the severe droughts in the study area were caused by a precipitation deficit of less than 3 months. The timescale was shorter—of 1 month—in southern China, the southern

parts of Yunnan and Chongqing, than that in the remaining areas. However, besides those due to a 1-month timescale, severe droughts due to a deficit of more than 2 months were more frequent in the northern parts of southwestern China than in the remaining areas.

(2) The distribution of the critical values of precipitation deficit showed clear regional differences, especially on the timescales of 1-2 months. Severe droughts occurred in the eastern parts of southwestern China and in north-central Guangxi if the monthly precipitation deficit was 60% and even 40% in some small pockets. In other areas, the critical amount of deficit was more than 80%. When the duration was 2 months, the critical value of the amount of deficit was 60%–80% in the western parts of southwestern China and the coastal areas of southern China and 40%–60% in most of the remaining areas. When the duration was 3 months, the critical value was mainly 40%–60%. When the duration was more than 3 months, the critical value was generally as low as about 40%. Overall, the critical value of the amount

FIGURE 8: Weighting precipitation deficit (colored dot, unit: %) and the percentage of droughts accounted for by each deficit (blank map, unit: %). The timescale is 1 month.

FIGURE 9: Weighting precipitation deficit (colored dot, unit: %) and the percentage of droughts accounted for by each deficit (blank map, unit: %). The timescale is 2 months (a) and 3 months (b).

of precipitation deficit for the eastern parts of southwestern China and most of the areas in southern China was lower than that for the western parts of southwestern China. The longer the timescale, the lower the critical value and the smaller the regional differences.

(3) Regional differences in the critical values of the length of the deficit and its amount were related to the differences in geographic position and climate. The western parts of southwestern China, especially the West Sichuan Plateau and north-central Yunnan, are at a higher elevation and the average temperatures at these higher altitudes are 10–12°C lower and evaporation is also 200–400 mm lower. Therefore, even in the absence of any precipitation deficit, the greater evaporation caused by the higher temperatures can accelerate

the development of drought in southern China and in the eastern parts of southwestern China, which is why even small amounts of precipitation deficit in these areas can cause severe droughts in a relatively short time. Zhang et al. [23] also found that the effect of temperature on the occurrence of droughts in southern China was greater than that in southwestern China. In addition, Hou et al. [39] indicated that due to the differences in climate, the timescales that can best reflect the impacts of precipitation deficit and the likelihood of droughts also vary from region to region. Droughts in the western parts of southwestern China, especially in Sichuan and northern Yunnan, were related to precipitation anomalies that lasted longer compared to those in southern China and the eastern parts of southwestern China—a pattern consistent

FIGURE 10: Relationship between cumulative timescales and cumulative precipitation deficit in different regions.

with the conclusions of the present study. To conclude, the differences in climate and changes in the climate were the main reasons for the differences in spatial distribution and severity of disasters. We propose to examine such regional differences in greater detail in the future.

Competing Interests

The authors declare that they have no competing interests.

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