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Research Article

Self-Organized Criticality of Rainfall in Central China

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Rainfall is a complexity dynamics process. In this paper, our objective is to find the evidence of self-organized criticality (SOC) for rain datasets in China by employing the theory and method of SOC. For this reason, we analyzed the long-term rain records of five meteorological stations in Henan, a central province of China. Three concepts, that is, rain duration, drought duration, accumulated rain amount, are proposed to characterize these rain events processes. We investigate their dynamics property by using scale invariant and found that the long-term rain processes in central China indeed exhibit the feature of self-organized criticality. The proposed theory and method may be suitable to analyze other datasets from different climate zones in China.

1. Introduction

China is not only a big country for its population but also a big agriculture one. Rain is the main source of irrigation water, and it plays a key role in the crop growing period. No rain will cause drought while storm may cause flood. To keep sufficient agriculture production sustainable, it is necessary to identify the role of the rain clearly and to understand the characteristics of the rain deeply. In particular, analyzing the rain in central China is more important because this region is the main crop source and the population density is very high.

Rain is liquid precipitation, as opposed to nonliquid kinds of precipitation such as snow and hail and so on. Rainfall is the result of the atmosphere movement, which is influenced by sun radiation, sea water evaporation, and earth rotation. In the fact, the long-term rain record is a time series which can be regarded as a random process. The rainfall process is actually a complexity system because there are too many influencing factors.

In previous studies, many mathematical methods have been applied to find the rainfall pattern, such as periodic, trend, change point, and fractal. Based on the last 1033 years historic data set, Jiang analyzed the temporal and spatial climate variability by using a "Mexican hat" wavelet transform [1]. Bordi used Standardized Precipitation Index (SPI) to assess the climatic condition of this region and applied principal component to capture the pattern of co-variability of the index at different gauge stations [2]. The results suggest that the northern part of east-central China is experiencing dry conditions more frequently from the 1970s onwards indicated by a negative trend in the SPI time series. Applying the binary cubic interpolation and optimal fitting method, Wang et al. set up a statistical model [3] and Yu used the application of gray and fuzzy methods [4], to make the rain forecast. Appling chaos dynamics theory on rainfall, Rodriguez-Iturbe et al. [5] and Wang et al. [6, 7] found that both the characteristics of the correlation integral and the Lyapunov exponents of the historical data give preliminary support to the presence of chaotic dynamics with a strange attractor. Using the correlation dimension method, the inverse approach of the nonlinear prediction method, and the method of surrogate data, Siva Kumar found that the rainfall data exhibit nonlinear behavior and possibly low-dimensional chaos, which imply that short-term prediction based on nonlinear dynamics might be possible [8, 9]. Ramirez used a feedforward neural network and resilient propagation learning algorithm to analyze the relation between the rain data and potential temperature, vertical component of the wind, specific humidity, air temperature, precipitable water, relative vorticity, and moisture divergence flux [10].

All the previous works are based on an assumption that the long-term rain process is stochastic or chaotic one. Nevertheless, the rain process is located at the brink between the chaos and determination. It is necessary to develop the new theory and methodology to address this context.

In recent years, a new perspective, which is called self-organized criticality (SOC), attracted applied mathematicians, meteorologists, climatologists, and environmentalists. Self-organized criticality is proposed by Bak et al. [11–15]. The term self-organized criticality refers to the tendency of many systems driven by an energy input at a slow and constant rate to enter states characterized by scale-free behavior. The statistics of the systems then resemble those of equilibrium systems near the critical point of a phase transition. Self-organized criticality is one of a number of important discoveries made in statistical physics and related fields over the latter half of the 20th century, discoveries which relate particularly to the study of complexity in nature. The most classical instances of SOC include the common natural phenomena, such as earthquakes and avalanches [16–19]. A rainfall event can be considered as an earthquake-like or an avalanche-like event [20, 21]. Further more, a long-term rain event series can be also seen as a similar event which is a complexity dynamics process and exhibits the feature of self-organized criticality.

Andrade analyzed long-term daily rain records of weather stations around the world with a special emphasis on the semiarid regions and found that there existed some evidences of SOC with these data [22]. Peters et al. investigated the European rain and fund it exhibits the feature of SOC [23–25]. However, up to now, we have not seen any report which related the China rain to SOC in the literature. In this work, we chose five meteorological stations in Henan, a central province of China, to try to find out the SOC evidence.

First of all we assume that the rainfall events that occurred in this region follow the power law distribution. And then based on the theory and method, we look for the SOC evidence through our calculating and analyzing. It is our aim for us to confirm the existence of SOC.

Henan is a leading province in grain, wheat, and oil seed output, and it is also an important producer of beef, cotton, pork, animal oil, and corn. With a population of approximately 93.6 million, Henan is the second most populous Chinese province after Guangdong. In this sense Henan is the big agriculture and population province in China. Precipitation, especially rain, has a dramatic effect on agriculture. All plants need at least some water to survive; therefore rain is important to agriculture. A regular rain pattern is usually vital to healthy plants; too much or too little rainfall can be harmful, even devastating to crops. Drought can kill crops and increase erosion while overly wet weather can cause harmful fungus growth. So studying the characteristics of the rainfall event is important to understand the dry and wet spell. It is consequently helpful to local flood and drought management.

2. Data Sets

We downloaded the data sets from China Meteorological Data Sharing Service System. These stations' geographic positions are displayed in Figure 1 in which Xinyang and Zhumadian are in the northern of Henan, Anyang and Zhengzhou in the northern part, Lushi in the western region. From the point of view of meteorological classification, the former two stations belong to humid subtropical climate zone while the later three stations are in the temperate climate zone.

The site name, site number, operation period and location are listed in Table 1. Station number is the general international code which is the WMO number. Obliviously the operation period is not equal in different stations. The format of degree, minute, and second is used to represent the location of the gauge station.

The original data sets should have contained the daily rain, but in some cases missing data may occur. Therefore these need to be pretreated by the method of interpolation before further analysis. After data pretreatment, we plot the five series in the Figure 2 whose horizontal axis represents the time of the rainfall day and vertical axis displays the daily rain amount (0.1 mm).

3. Method of Analysis

3.1. Scale Invariant. One of the great successes of physics in the last decades has been in the understanding of phenomena with fluctuations over many scales. In high-energy physics, critical phenomena and hydrodynamics it is often possible to establish the existence of a scaling or scale invariant regime in which the fluctuation (Δx) in the field of interest (x) at small scale Δt and at large scale $\lambda\Delta t$ $(\lambda > 1)$ is amplified by the factor $\lambda^{-\tau}$, where τ is the scaling parameter. This may be written more concisely as

$$\Delta x(\lambda\Delta t) = \lambda^{-\tau}\Delta x(\Delta t), \quad (1)$$

where $\Delta t = t_1 - t_0$, $\Delta x(\Delta t) = x(t_1) - x(t_0)$, $t_2 = t_0 + \lambda(t_1 - t_0)$, $\Delta x(\lambda\Delta t) = x(t_2) - x(t_0)$, and equality is understood in the sense of probability distributions, that is, $F(X) = F(Y)$ if $\Pr(X > c) = \Pr(Y > c)$ for all c, Pr means Probability.

In Section 1, we said that our work objective is to find the evidence of the SOC of rain process in central china. To look it out, we need construct mathematical models to mine the relations between the SOC and the long-term rain records. In the literatures on the SOC, power law distribution (scaling or scale invariance) is often used as a tool to prove a complexity dynamic process with the feature of SOC. To reveal the existing of SOC in the rain process, in the beginning we define a rain event as a sequence of consecutive nonzero measurements of the rain rate. Consequently, we use 3 variables, which contain rain duration, drought durations and accumulated rain amount to describe the feature of rain event in the region.

The probability density function of a physical variable X (such as rain duration,drought duration and accumulated rain amount in a rainfall event) is denoted by $n(x)$, which

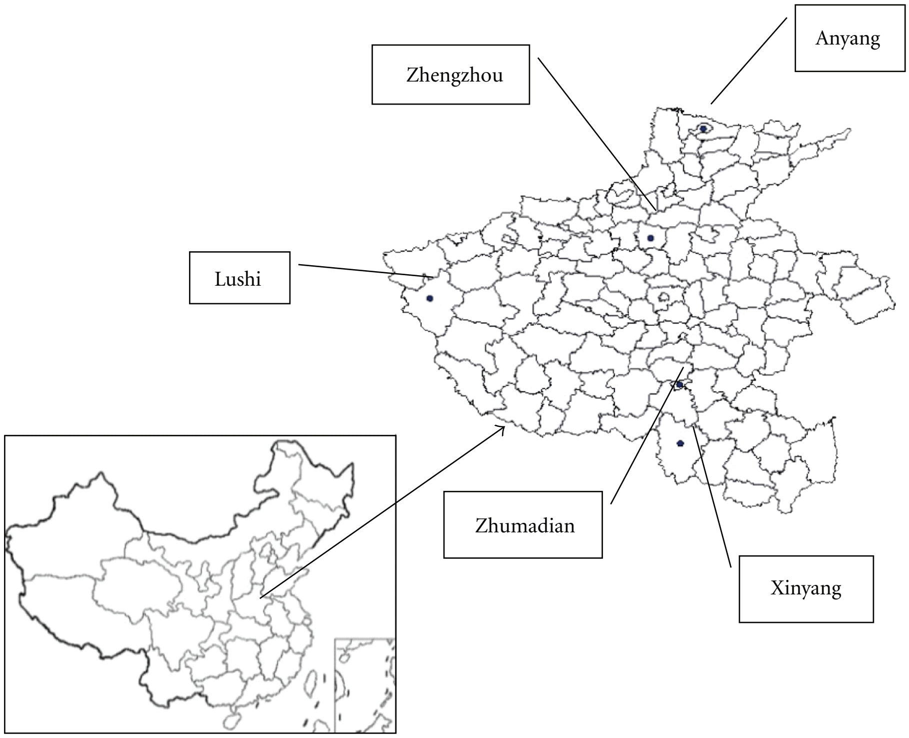

Figure 1: Distribution of stations, named Anyang, Zhengzhou, Lushi, Zhumadian, and Xinyang.

Table 1: Observation sites with station number, corresponding time periods estimated, and location.

Site name	Station number	Operation period	Location	
Zhengzhou	57083	195101–200712	34° 43′N	113° 39′E
Anyang	53898	195102–200712	36° 07′N	114° 22′E
Zhumadian	57290	195801–200712	33° 00′N	114° 01′E
Xinyang	57297	195101–200712	32° 08′N	114° 03′E
Lushi	57067	195207–200712	34° 03′N	111° 02′E

Longitude and latitude of the location is represented as degree and minute.

accumulated probability distribution (PDF) is $\widetilde{N}(x)$. PDF can be defined as

$$\widetilde{N}(x) = \int_{x}^{x_M} n(x)dx, \tag{2}$$

where x_M is the maximum value in the data set. By using the integrated description instead of histograms we avoid data fluctuations in the low (high) value regime induced by the choice of logarithmic. If $n(x) \propto x^{-\tau}$, $x_M \to \infty$ and $\tau \to 1$, then $\widetilde{N}(x) \propto x^{-\tau+1}$. Our rainfall data are generally confined to ranges $1 < I < 200$ days and $0.1\,\text{mm} < x < 400\,\text{mm}$, while higher values are observed only in extreme situations. Therefore, we cannot replace M by ∞ in (2) and obtain

$$N(x) = \frac{\widetilde{N}(x)}{x} \propto \frac{1}{x^{\tau}}\left[1 - \left(\frac{x}{x_M}\right)^{\tau-1}\right]. \tag{3}$$

Thus, the log-log plot of $N(x)$ versus x definitely departs from a straight line as $x \to x_M$.

3.2. Algorithm. Based on the principle of scale invariant, we develop 2 algorithms corresponding to rain duration, drought duration and accumulated rain amount, in which first algorithm is about the former two items and the second is about the accumulated rain amount.

3.2.1. Procedure for Rain Duration and Drought Duration. Rain duration is the life time of a successive rainfall, and drought duration is the waiting time between two rain events. Let RD and DD stand for rain duration and drought, respectively. Their distribution densities are discrete which are listed as shown in Table 2.

To test the scaling of rain duration and drought duration in central China, analysis can be conducted by the following procedure.

Algorithm 1 (Accumulated probability distribution computation and plot of rain duration and drought duration). We have the following:

Step 1. Wash and treat the original data.

TABLE 2: Distribution model of rain duration and drought duration.

RD/DD	x_1	x_2	$\cdots$	x_M
$n(x)$	$n(x_1)$	$n(x_2)$	$\cdots$	$n(x_M)$
$\widetilde{N}(x)$	$\sum_{i=1}^{M} n(x_i)$	$\sum_{i=2}^{M} n(x_i)$	$\cdots$	$\sum_{i=M}^{M} n(x_i)$
$N(x)$	$\left(\sum_{i=1}^{M} n(x_i)\right)/x_1$	$\left(\sum_{i=2}^{M} n(x_i)\right)/x_2$	$\cdots$	$\sum_{i=M}^{M} n(x_i)/x_M$

x_i stands for the length of every rain or drought event. M is the longest time period.

Step 2. Plot the daily rain size on the rain date (see Figure 2).

Step 3. Count the numbers of every kind of rain events and assign $n(x)$ the number listed in the second row of Table 2.

Step 4. Calculate the accumulated number $\widetilde{N}(x) = \sum_{i=j}^{M} n(x_i)$, $j = 1, 2, \ldots, M$ and list it in the third row.

Step 5. Calculate the number density $N(x) = (\sum_{i=j}^{M} n(x_j))/x_j$ of rain event corresponding to the fourth row and list it in the fourth row.

Step 6. According to formula (3), we take the logarithm of the first and fourth row. By the linear regression technology, we will obtain τ.

Step 7. Make the double-log distribution plot.

3.2.2. Procedure for Accumulated Rain Amount. In the present paper, the accumulated rain amount, which is symbolized as ARA, represents the total rain amount in a single rain event. Then, based on Step 1 and Step 2 in Algorithm 1, the procedure of ARA analysis can be followed by Algorithm 2 below.

Algorithm 2 (Accumulated probability distribution computation and plot of ARA). We have the following:

Step 1. By calculating the ARA we get a new ARA series $y_1, y_2, \ldots, y_N$, where N stands for the number of the rainfall event in the long-term record.

Step 2. Let $y_{\min} = \min(y_1, y_2, \ldots, y_N)$, $y_{\max} = \max(y_1, y_2, \ldots y_N)$, and partition the closed interval $[y_{\min}, y_{\max}]$ into subinterval $[y, y + \Delta y]$. Here, Δy can be computed by using the following equation:

$$\frac{y + \Delta y}{y} = 10^{1/5}. \tag{4}$$

Step 3. If S is the number of all the subintervals, we calculate the times of the occurrences of $y_1, y_2, \ldots y_N$ in every interval and note them $n(s), s = 1, 2, \ldots, S$.

Step 4. Calculate the accumulated number $\widetilde{N}(s) = \sum_{s=j}^{S} n(s)$, $j = 1, 2, \ldots S$.

Step 5. Calculate the number density $N(s) = (\sum_{s=j}^{S} n(s))/\Delta s_j$.

Step 6. Take the logarithm of $N(s)$ and left end point of $[y, y + \Delta y]$. By the linear regression technology, we will obtain τ in terms of Formula (3).

Step 7. Make the double-log distribution plot.

4. Result and Discussion

According to the steps of Algorithm 1, the long-term rains are shown in Figure 2. Xinyang station and Zhumadian station, which are located in the southern part of Henan Province, are plotted above. Contrast Anyang station, Zhenzhou station, and Lushi station, which are located in the northern part of this province.

4.1. Rain Duration and Drought Duration. Corresponding to Table 2, the calculation results of rain duration are listed in Table 3. For the dataset is too large, here we only list out Zhenzhou station's data.

The computation results about rain duration and drought duration show that the rainfall times and the rain duration, the drought days and the drought duration exhibit the power law relation. Taking the logarithm value of number density as the vertical axis and the logarithm value of the rain duration as horizontal axis, we find that the distribution of the rain duration number in Xinyang station, Zhumadian station, Zhengzhou station, and Lushi station is similar with their function profile (see Figure 3) while Anyang's number density of rain duration exhibits the different feature. The scale-free region ranges from 1 to 10 in Anyang and from 1 to 11 in other places. Here, $\tau_{\text{anyang}} = -1.35$, other τs fluctuate around -1.68. Influenced by the monsoon climate, the rain season begins in the early June and ends in the lately September. In fact, the Anyang is this region where the rain duration is the shortest in Henan province.

Looking at Figure 3 and Figure 4, it seems that the number density of drought duration displays the same distribution characteristics with the rain durations. Actually, the number density of rain duration is different in some aspects, such as the maximum time period and scaleless region. Furthermore, attention should be paid to the number density of drought duration in Zhengzhou and Anyang (see Figure 5). The scale region of Anyang station ranges from 1 day to 100 days, and Zhengzhou's scaling left end point closes to 100 but Xingyang's and Zhumadian's are about 50.

Here, $\tau_{\text{xinyang}}, \tau_{\text{xinyang}} \approx -1.71$, and other τ is about -1.5.

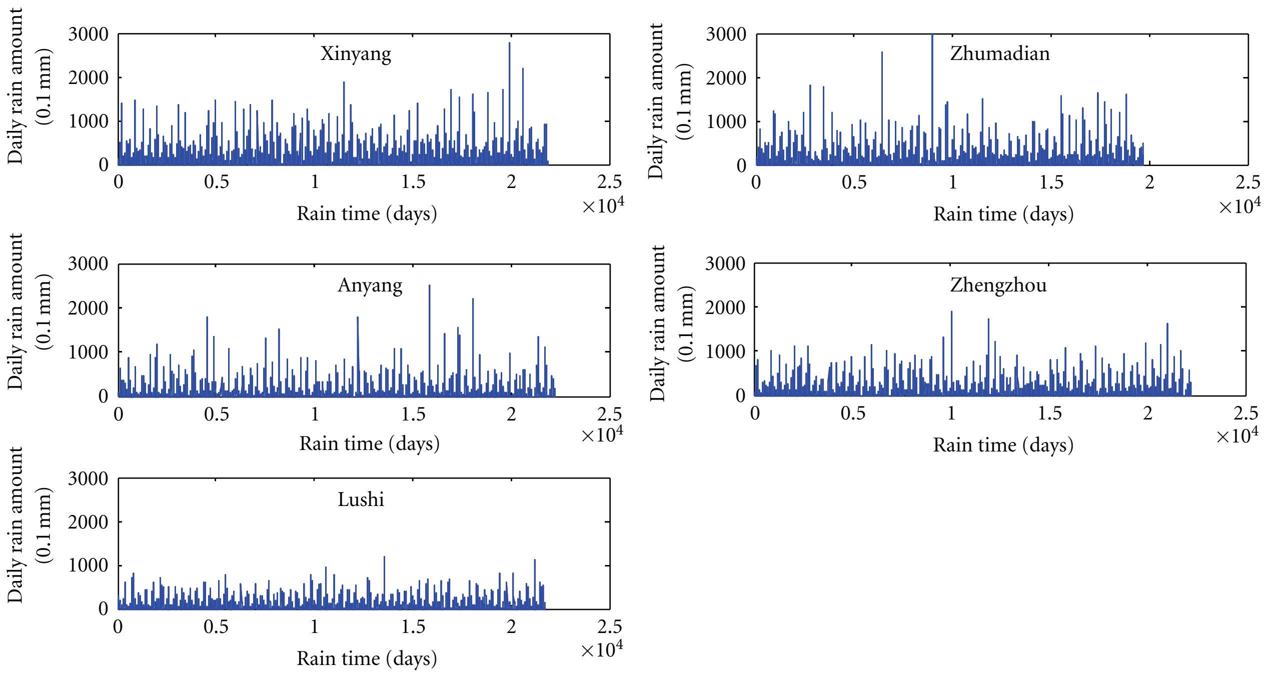

Figure 2: Plot of five rain series in Henan province.

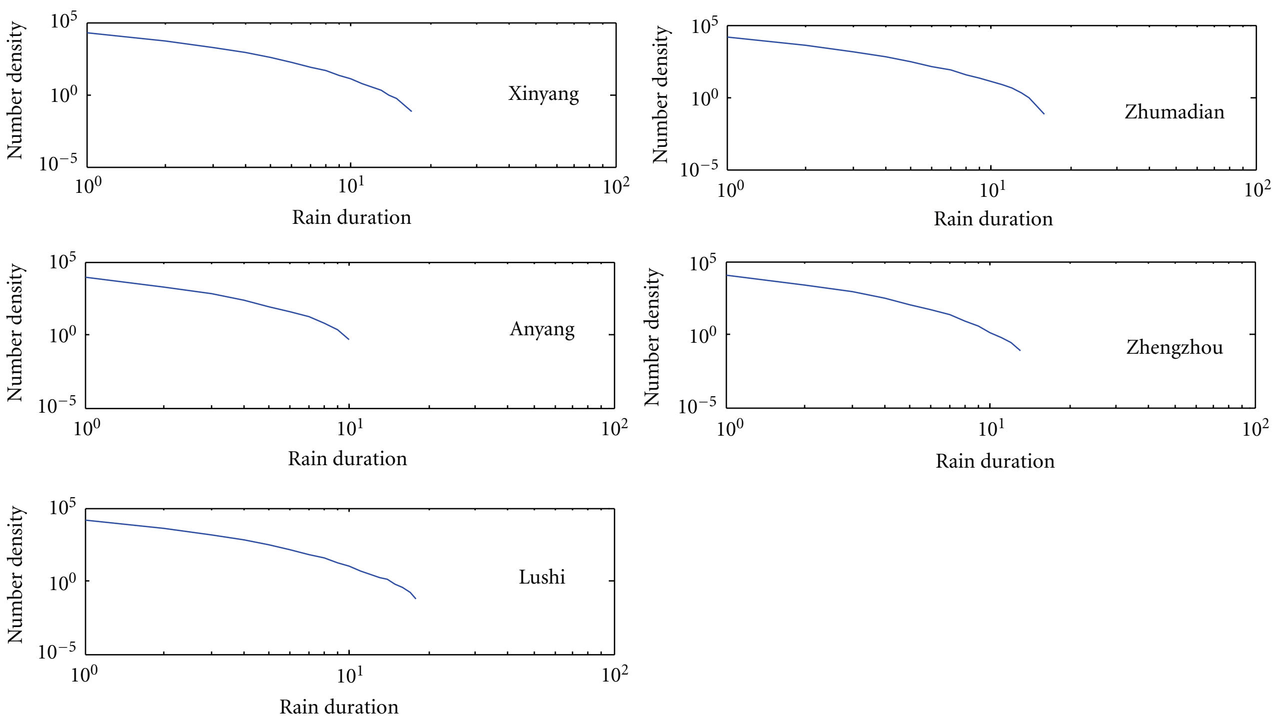

Figure 3: Log-log plot of the probability number density for rain duration.

4.2. Accumulated Rain Amount. Comparing with the analysis on rain duration and drought duration, it is more difficult to understand the behavior characteristics of long-term ARA dynamics process. To test if the ARA is scale invariant, we calculated the ARA number density in the partitioned intervals in terms of Algorithm 2.

The results show that all five series follow the power law relation in the scale range from 0.1 mm to 60 mm. Here $\tau_{\text{xingyang}} = -1.61$, $\tau_{\text{zhumadian}} = -1.63$, $\tau_{\text{anyang}} = -1.72$, $\tau_{\text{zhengzhou}} = -1.52$, $\tau_{\text{lushi}} = -1.55$. The ARA number density distributions of Xinyang and Zhumadian displays the similar profile since they are in the same

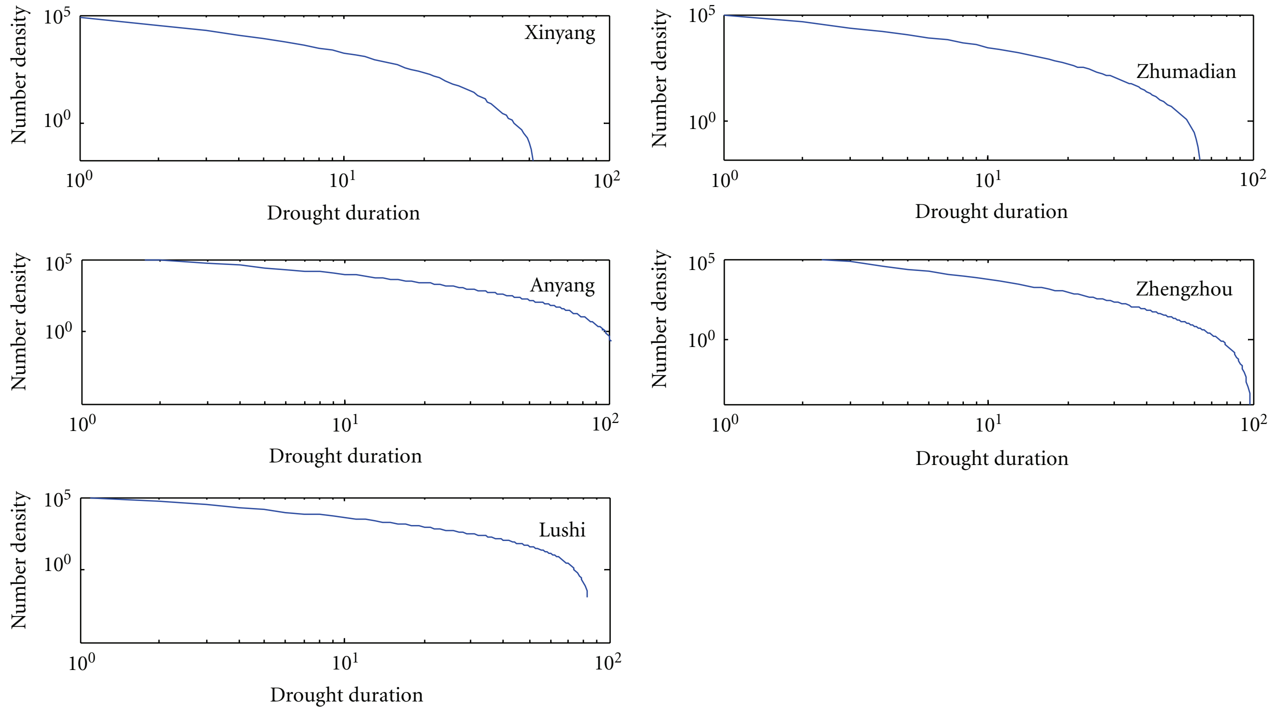

FIGURE 4: Log-log plot of the probability number density for drought duration.

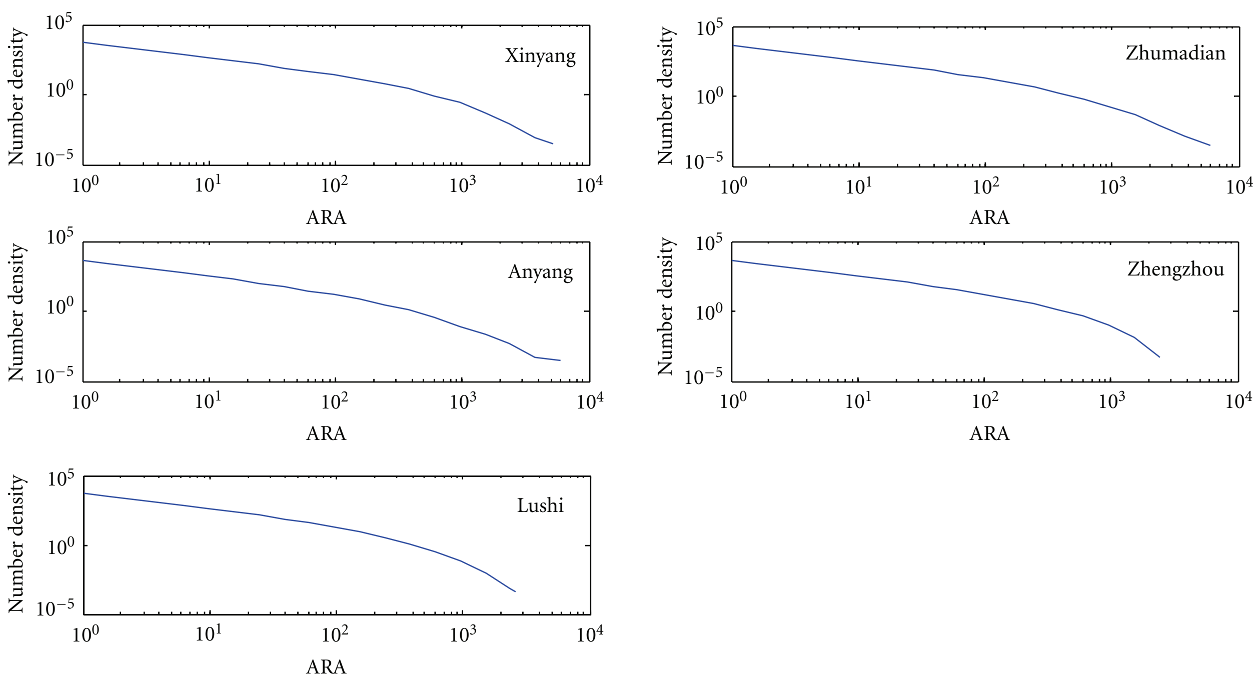

FIGURE 5: Log-log plot of the probability number density for accumulated rain amount.

climate classification region, the subtropical zone. Like Section 4.1, the feature of ARA in Anyang station is also different from the other stations. Although Lushi station is located in the western mountain region, however, the ARA behavior characteristic in Zhengzhou station is similar to it.

4.3. Discussion. In Sections 4.1 and 4.2 we have investigated the long-term series of precipitation records and succeeded in finding the evidence for power law distribution even though the five stations are located in different position in central China. This implies that our guess (i.e., the rainfall in central China takes on the feature of SOC) is right. This also

Table 3: Days of RD and DD; ARA (in 0.1 mm) per rain event.

RD	N (RD)	DD	N (DD)	DD	N (DD)	S.N	ARA	S.N	ARA	S.N	ARA
1	4309	1	14586	37	44	1	48	37	92	...	...
2	2427	2	11564	38	35	2	92	38	42	2501	15
3	1418	3	9553	39	27	3	7	39	18	2502	60
4	812	4	7615	40	21	4	61	40	55	2503	1
5	463	5	6205	41	17	5	39	41	14	2504	212
6	257	6	5084	42	13	6	8	42	20	2505	26
7	141	7	4179	43	11	7	6	43	88	2506	80
8	78	8	3448	44	9	8	3	44	1	2507	9
9	42	9	2868	45	8	9	42	45	320	2508	66
10	26	10	2425	46	7	10	35	46	95	2509	297
11	17	11	2072	47	6	11	75	47	56	2510	60
12	10	12	1783	48	5	12	58	48	296	2511	8
13	6	13	1542	49	4	13	780	49	68	2512	10
14	4	14	1333	50	3	14	85	50	38	2513	18
15	2	15	1161	51	2	15	7	51	93	2514	53
16	1	16	1105	52	1	16	278	52	16	2515	51
17	0	17	879	53	0	17	44	53	25	2516	223
18	0	18	762	54	0	18	468	54	121	2517	299
19	0	19	660	55	0	19	18	55	1	2518	66
20	0	20	566	56	0	20	555	56	653	2519	437
21	0	21	486	57	0	21	50	57	43	2520	213
22	0	22	421	58	0	22	59	58	30	2521	104
23	0	23	365	59	0	23	34	59	29	2522	11
24	0	24	317	60	0	24	21	60	79	2523	605
25	0	25	278	61	0	25	213	61	52	2524	381
26	0	26	241	62	0	26	225	62	237	2525	1561
27	0	27	211	63	0	27	13	63	1	2526	237
28	0	28	187	64	0	28	96	64	21	2527	355
29	0	29	164	65	0	29	11	65	8	2528	125
30	0	30	143	66	0	30	2	66	384	2529	267
31	0	31	125	67	0	31	812	67	47	2530	398
32	0	32	109	68	0	32	198	68	7	2531	422
33	0	33	95	69	0	33	7	69	15	2532	25
34	0	34	81	70	0	34	146	70	111	2533	0
35	0	35	68	71	0	35	189	71	71	2534	0
36	0	36	56	72	0	36	8	72	76	2535	0

supports the view that atmospheric dynamics is governed, at least in part, by SOC.

As described in the introduction, the concept of SOC refers to the state of nonequilibrium systems driven by slow constant energy input to organize themselves into critical systems. The intermediately stored energy is eventually released in sudden bursts with no typical scale. From this point of view, rainfall events which occur in the central China are not very different from those ones in the other place. Like earthquakes, a rainfall event is driven by a slow and constant energy input from the sun and water is evaporated from the Western Pacific Ocean. The energy is stored in the form of water vapor in the atmosphere. It is then suddenly released in bursts when the vapors condense to water drops. The power-law distribution of the number density of rain events is equivalent to the Gutenberg-Richter law for earthquakes.

Although there are different geographic coordinates at the five stations, these τs show little change because the five stations are neighborhoods in one province after all. Except for the topography and landform the driving factors of rainfall, such as the sun radiation and the pattern of atmospheric circulation are nearly the same.

5. Conclusion

Testing the hypothesis, the existence of self-organized criticality in the long rain process in central China is our objective in this work. By calculating the number density of the rain duration, the drought duration, and the accumulated rain amount, we found that the relationship between the number density functions and rain duration, drought duration and accumulated amount exhibits the feature of power law. In other words, we have looked out the evidence of self-organized criticality in the long-term rain processes in central region of China. It is turned out that the long dry and wet process is indeed the complexity dynamics process.

Henan province is in the climate transition zone where the climate changes from the southern humid subtropical monsoon region to the northern semiarid temperature monsoon. It is also the topography transition zone. The western region is mountain and the eastern is the great plain. Because of these reasons, the weather and the climate change drastically in a year and interyears. This point has also been turned out from our results and plots. The feature of wet and dry spell is significantly different between Anyang station and Xinyang station.

In this work we only studied five meteorological stations due to the limitation of datasets. And the minimum time interval is a day which appears to be not small enough for the analysis of rainfall event. We will therefore collect more data sets in central China and other regions in the future work. The self-organized criticality needs to be tested in a small temporal interval and in a larger spatial scale, such as in the level of hour or second and in the level of the whole country. Furthermore, Algorithm 2 proposed should be improved on the number density computation of accumulated rain amount. The concept of number density of duration and intension should be redefined over and over again in the future work.

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