Analysis of the spatio-temporal propagation of drought over Eastern China using complex networks

Analyse de la propagation spatio-temporelle de la sécheresse sur l'est de la Chine à l'aide de réseaux complexes

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Abstract. Understanding of the spatio-temporal propagation of drought is a challenging issue as the hydro-climatic processes are inter-connected. Recent developments in network theory offer new avenues to study the propagation of drought. Three metrics that quantify the strength, dominant orientation and distance of droughts are employed to investigate the spatio-temporal propagation. The results show that (1) the network approach based on the event synchronization is a useful tool to study the propagation of drought; (2) The drought events occurring in the south of the study area are more likely to spread outward, and the drought events occurring in the midwestern regions are more likely to be affected by drought events in other regions; (3) The dominant position of drought transmission in the study area has obvious regional characteristics. The midwestern regions are more susceptible to the influence of drought events in the western regions, while other regions are more likely to spread drought events to the inside world. The findings of this paper could help researchers to initially understand the propagation of spatio-temporal droughts over Eastern China.

Résumé. La compréhension de la propagation spatio-temporelle de la sécheresse est un problème difficile, car les processus hydro-climatiques sont interconnectés. Les développements récents de la théorie des réseaux offrent de nouvelles pistes pour étudier la propagation de la sécheresse. Trois indicateurs qui quantifient la force, l'orientation dominante et la distance des sécheresses sont utilisées pour étudier la propagation spatio-temporelle. Les résultats montrent que (1) l'approche réseau basée sur la synchronisation des

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événements est un outil utile pour étudier la propagation de la sécheresse ; (2) les épisodes de sécheresse survenant dans le sud de la zone d'étude sont plus susceptibles de se propager vers l'extérieur, et les épisodes de sécheresse survenant dans les régions du Midwest sont plus susceptibles d'être affectés par des épisodes de sécheresse dans d'autres régions ; (3) la position dominante de la transmission de la sécheresse dans la zone d'étude présente des caractéristiques régionales évidentes. Les régions du Midwest sont plus sensibles à l'influence des épisodes de sécheresse dans les régions occidentales, tandis que d'autres régions sont plus susceptibles de propager les épisodes de sécheresse dans le monde intérieur. Les résultats de cet article pourraient dans un premier temps aider les chercheurs à comprendre la propagation des sécheresses spatio-temporelles dans l'est de la Chine.

1 Introduction

Drought is considered by many to be the most complex but least understood of all natural hazards, affecting more people than any other hazard [1,2]. Affected by global climate change, meteorological and hydrological factors around the world are undergoing significant changes, and their changes have exceeded the natural fluctuations of the Earth itself, resulting in a significant increase in the frequency of drought events, deterioration in duration and severity. As a typical extreme weather event, drought has strong nonlinear characteristics in its temporal and spatial evolution and propagation. It is extremely difficult to analyze the drought processes from the perspective of its physical mechanism. Complex networks theory provides a new perspective to explore some properties that cannot be obtained by traditional methods, focusing on the topological structure. Many discoveries of complex networks up to now, such as basic models of network topology, propagation mechanisms of complex networks, and the synchronization behavior of complex dynamical networks, make complex network theory widely used in all fields, including in large power networks, transportation networks, social networks and spreading networks [3-8]. For the hydrological field, the available studies mainly focus on the following three aspects [9]: 1) The evolution of extreme events, such as heatwaves or rainfall. The event synchronization method (ES) is employed to quantify the synchronicity of extreme events. Network edges are placed between two nodes if the corresponding synchronization values are significant. Then, the indicators in complex networks, such as degree, clustering coefficient, closeness centrality and betweenness centrality, are adopted to analyze the spatial or spreading characteristics of extreme events [10–14]. 2) The detection of time-series variability, including precipitation or temperature series. The coarse graining process is employed to convert the data series into character sequences. A string consists of several characters represent nodes, and network edges are placed between two nodes according to the time sequence. Then, clustering coefficient, average path length, and the concept of a scale-free or small-world network is used to reveal climate change [15,16]. 3) Spatial connections of rainfall or runoff. Most studies focused on the spatial connections, temporal scale or network architecture of rainfall networks [17,18] or runoff networks to optimize hydrometric monitoring system design [19,20].

However, few studies focus on drought using complex network, especially the East Asian monsoon region affected by frequent monsoon activities. This provides the motivation for the present study. Therefore, in this study, we apply the concept of complex network and event synchronization to analyze the propagation of spatio-temporal droughts over Eastern China, which provide a new perspective for the study of drought propagation.

2 Materials and Methods

2.1 Data Sources

The data is obtained from Project Management Service supported by Max Planck Institute for Meteorology, which contains a variety of climate data, including daily precipitation, daily maximum temperature, daily minimum temperature, daily average temperature, daily average wind speed, daily relative humidity and sunshine time. We have extracted the gridded data for the Eastern China (Fig. 1) with a horizontal resolution of 0.5 degree from 1961 to 2015 and there are 619 grid points in the study area. In order to verify the accuracy of the data set, we interpolate the meteorological data obtained from observation stations (available from the website of China meteorological data service center, http://data.cma.cn) to the same horizontal resolution. The comparison shows that there is little difference.

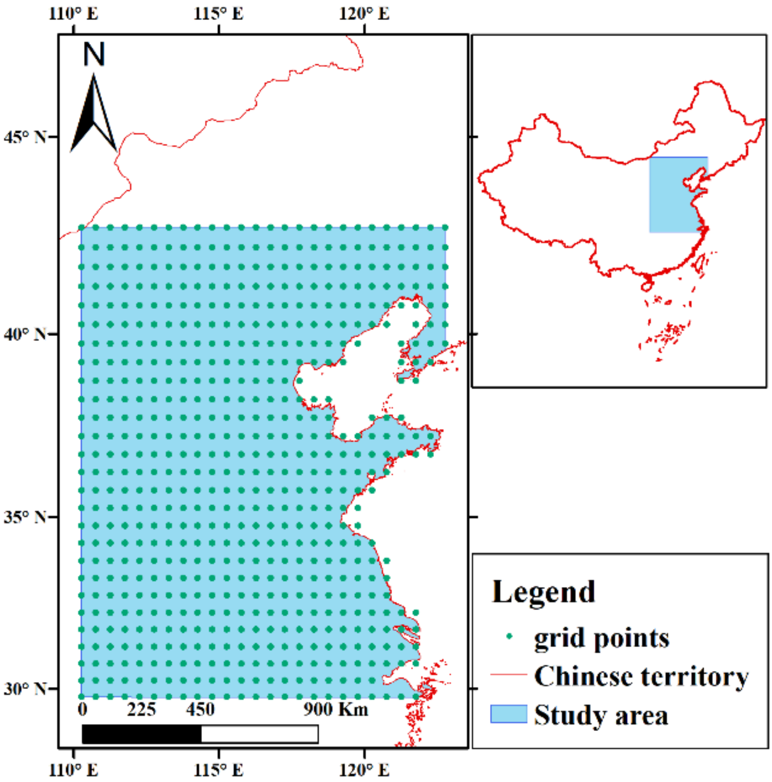

Fig. 1. Overview of the study area and research stations.

2.2 Complex network methodology for droughts propagation analysis

We employed event synchronization methodology (ES) to determine association between drought events occurring at different spatial locations. Quian et al. propose event synchronization to measure synchronization and time-delay patterns between signals. It is based on the relative timings of events in the time series, defined as local maxima. The degree of synchronization is obtained from the number of quasi-simultaneous appearances of events, and the delay is calculated from the precedence of events in one signal with respect to the other [21]. Malik et al. introduced this method to analyze the relationship between extreme events occurring in different spatial locations [22]. Event synchronization allows a dynamic delay between two extreme events at different spatial locations to calculate the degree of agreement between the two events in time. As a result, this metric does not assume any probability distribution to be followed by the underlying data. In addition, the method explicitly considers the interval time period, so it is very suitable for extreme events such as data with uneven time intervals. The dynamic delay is estimated as

$$\tau_{lm}^{ij} = \frac{\min\left(t_l^i - t_l^{i-1}, t_l^{i+1} - t_l^i, t_m^j - t_m^{j-1}, t_m^{j+1} - t_m^j\right)}{2} \tag{1}$$

Where t_l^i represents the start time when the extreme event i has occurred in the region l. $t_l^i - t_l^{i-1}$ represent the interval between two consecutive drought events in location l. τ_{max} is employed to represent a threshold of a maximum delay, which could exclude unreasonable long dynamic delays between the extreme events occurring at two locations. When $0 < t_l^i - t_m^j < \tau_{lm}^{ij}$ and $0 < t_l^i - t_m^j < \tau_{max}$, it can be considered that the event i at location l and the event j at location m are synchronized, and i is ahead of j:

$$S_{lm}^{ij} = \begin{cases} 1, & 0 < t_l^i - t_m^j < \tau_{lm}^{ij}, 0 < t_l^i - t_m^j < \tau_{max} \\ 0, & otherwise \end{cases} \tag{2}$$

ES_{lm} represents the relative number of drought events at *l* preceding event at *m*, which represents how likely an extreme event in location l can propagate to location m. ES_{lm} is estimated as:

$$ES_{lm} = \frac{\sum_{ij} S_{lm}^{ij}}{n_l} \tag{3}$$

Where $n_l$represents the total number of drought events at *l*. Similarly, ES_{ml} is estimated as:

$$ES_{ml} = \frac{\sum_{ij} S_{ml}^{ij}}{n_m} \tag{4}$$

We repeat the above steps for each pair of grid points to derive a matrix of ES with the dimension of N×N (N represents the number of grid points).

The bootstrapping method is employed to extract statistically significant values. We select the 0.05 significance level to estimate EST_{lm} and EST_{ml}. Repeat the above steps for each pair of grid points to derive a matrix of EST with the dimension of N×N. If an ES value is greater than EST, it means the value is statistically significant at the desired significance level:

$$C_{lm} = \begin{cases} ES_{lm,l\neq m}, & if\ ES_{lm} > EST_{lm} \\ x, & otherwise \end{cases} \tag{5}$$

Obviously, C is a weighted-directed adjacency matrix of dimension N×N. The non-zero value (also called edge) in C represents the possibility of propagation of drought between two locations.

Then three metrics are employed to characterize the strength, dominant orientation and propagation distance of the droughts, which were proposed by Goutam Konapala et al. (more details see [23]).

(1) The strength metric is defined by the concept of weighted and directed degree. Strength metric can be expressed as:

$$Sr_l^{out} = \sum_{m=1}^{N} C_{lm} \text{ and } Sr_l^{in} = \sum_{m=1}^{N} C_{lm} \tag{6}$$

Where N represents the number of grid points, Sr_l^{out} and Sr_l^{in} represent outward-strength and inward-strength at l. Obviously, the higher Sr_l, the higher the influence of the location l is in drought propagation. The difference of Sr_l^{out} and Sr_l^{in} (ΔSr_l) indicate the sequence of events at location l in the propagation.

(2) To describe the dominant orientation of drought propagation, the orientation angle range (2π) is classified into 8 orientations (each of 0.25π). The orientation of the maximum absolute value of ΔSr_l is defined as the dominant orientation:

$$Or_l = argmax(abs(Sr_l^{in}(\phi) - Sr_l^{out}(\phi))) \tag{7}$$

(3) the distance metric is defined as the mean geographical distance along the dominant orientation at location:

$$Dr_l^{out} = \frac{\sum_{m\epsilon Or_l^{out}} Di_{lm}}{n_{Or_l^{out}}} \text{ and } Dr_l^{in} = \frac{\sum_{m\epsilon Or_l^{in}} Di_{ml}}{n_{Or_l^{in}}} \tag{8}$$

Where n_{Or_l} represents the number of the non-zero elements in the dominant orientation, *Di* represents the geographical distance between two location.

3 Results

By utilizing OITREE (An Objective Identification Technique for Regional Extreme Events) [24], 179 regional drought events were identified in the study area. Then we constructed the drought network using event synchronization methodology and the threshold τ_{max} was determined as 10 days. According to the directed and weighted adjacency matrix C, there are 164680 edges among the 619 grid points, accounting for 42.98% of the maximum possible number of edges. The average degree is 266.04, which indicates that the network is quite connected.

The outdegree and indegree distribution of the drought network (Fig. 2) indicates that the standard deviation of indegree is greater than that of outdegree. It can be inferred that drought events occurring at most grid points drought spread among them, that is, the probability of the drought events of these nodes being transmitted and transmitted is relatively close. There are also some grid points that tend to spread inward, that is, drought events in these nodes are spread from other locations.

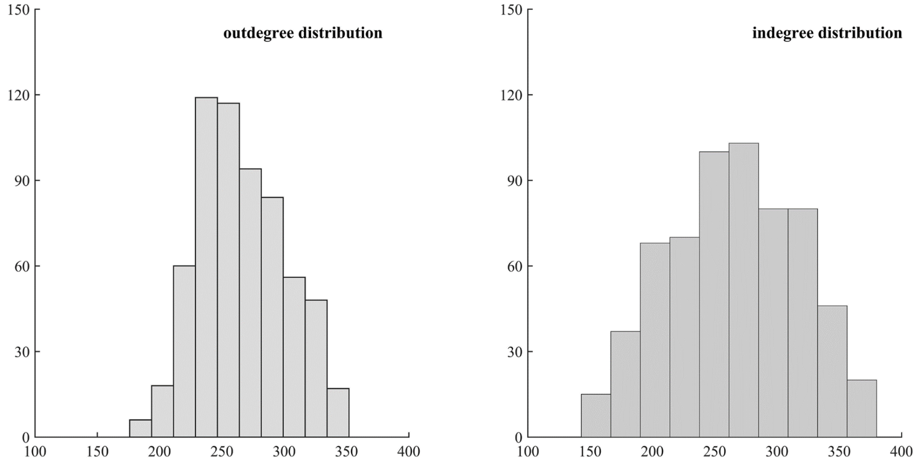

Fig. 2. Frequency of out-degree and in-degree.

For outward-strength (Fig. 3A), The higher outward-strength values in the south-central part of the study area indicate that the above locations play a relatively "important" role in the drought propagation. Drought events occurring in these areas are more likely to spread to other areas. Different from outward-strength, midwestern part of the study area has higher inward-strength values, which indicates that these areas are more vulnerable to drought events occurring in other areas (Fig. 3B).

Figure 3C shows the difference between outward-strength and inward-strength (ΔSr_i), midwestern part of the study area has higher positive value of ΔSr_i and they are the sinks of the networks. Droughts occurring at other locations may propagate to these regions. The regions with negative values (south of the study area) are the sources of the network, and it is more likely for the extreme events to start at that particular location and subsequently propagate to other locations.

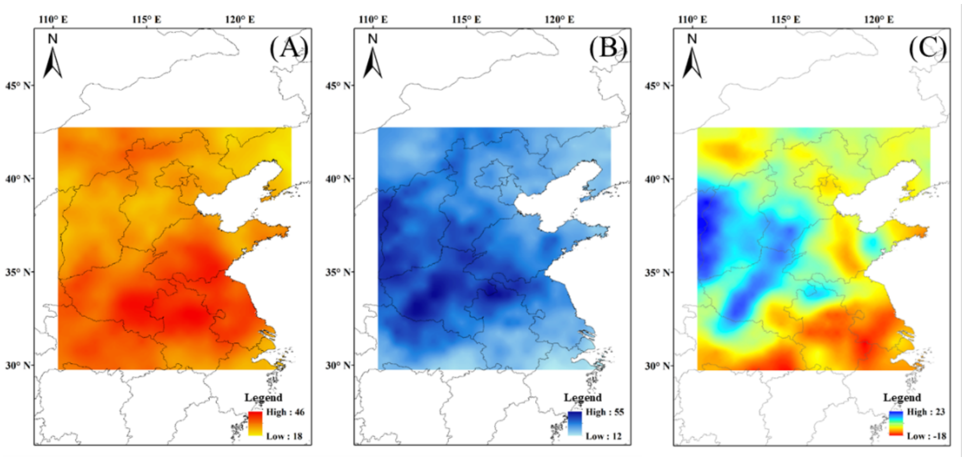

Fig. 3. Spatial distribution of outward-strength (A), inward-strength (B), and difference between outward-strength and inward-strength (C).

The distribution of dominant orientation is illustrated in figure 4. Blue arrows represent inward-orientation and red arrows represent out-orientation. It can be observed that drought events occurring at midwestern part of the study area tend to propagate from west-northwest (WNW), west-southwest (WSW) north-northwest (NNW) directions. Other locations propagate drought events to the central part of the study area. However, it is worth noting that the orientation shown in the figure 4 does not mean that the propagation is from a certain area to an adjacent area. It only indicates that the drought event in some place spreads to a certain area in the dominant propagation direction, not including the propagation distance.

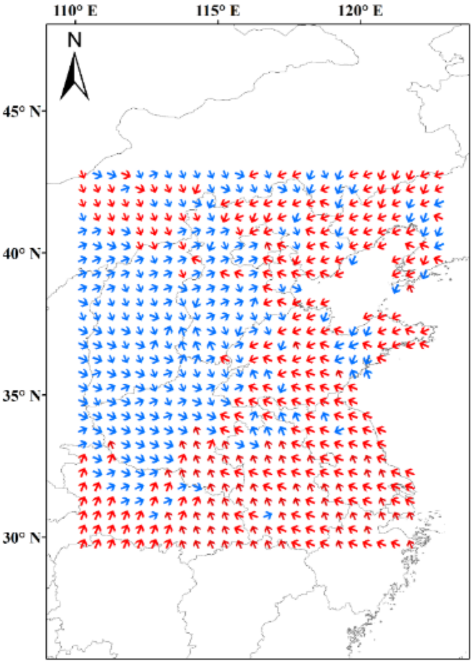

Fig. 4. Distribution of orientation (blue: inward-orientation; red: outward-orientation).

It is worth noting that the drought network is constructed based on the event synchronization methodology. The relationship between extreme droughts occurring at different locations could be categorized as functional connectivity, which means it is possible that the droughts occurring far apart could vary in a synchronized manner. The distribution of outward-distance and inward-distance are illustrated in figure 5. The farthest propagation distance reaches 1000 km and the central part of the study area has a small propagation distance. The possible reasons are: 1) the spatial connection of grid points is quite close (the average degree reaches 266.04); 2) the average geographical distance between the middle points and other points is relatively small. Nevertheless, the figure still shows some interesting results. For example, Jianghan Plain (in the southeast of the study area) has a high outward-distance and its dominant orientation is NNE, which means that the droughts occurring here may propagate over 1000km along the NNE orientation.

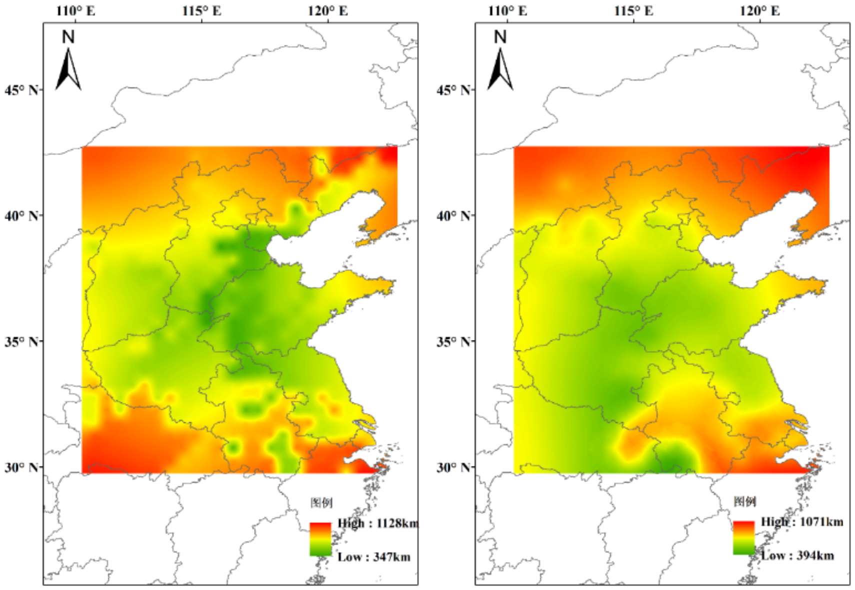

Fig. 5. Distribution of outward-distance and inward-distance.

4 Results

This study constructed the drought network of Eastern China based on the event synchronization methodology. Three metrics that quantify the strength, dominant orientation and distance of droughts are employed to investigate the spatio-temporal propagation. The following conclusions can be drawn from this study:

(1) Midwestern part of the study area are the sinks of the networks, while south of the study area are the sources of the network;

(2) Drought events occurring at midwestern part of the study area tend to propagate from west-northwest (WNW), west-southwest (WSW) north-northwest (NNW) directions. Other locations propagate drought events to the central part of the study area;

(3) The spatial connection of grid points is quite close and long-distance propagation droughts are common.

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