# Postprint: Analysis of Evolutionary Characteristics of Drought Events in China Based on Three-Dimensional Identification

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## Abstract

China is one of the countries most severely affected by drought worldwide, with frequent drought events causing serious impacts on its economic and social development and ecological environment. To analyze the spatiotemporal characteristics of drought events over the past 40 years, this study employs a three-dimensional clustering algorithm to identify drought events in China from 1981 to 2020 and quantitatively analyze their spatiotemporal dynamic evolution processes, based on the essential nature of spatiotemporal linkages in drought events. The main conclusions are as follows: The three-dimensional clustering algorithm can effectively identify drought events and their dynamic evolution processes. From 1981 to 2020, China experienced 102 drought events lasting two months or longer; spatially, drought event trajectories tend to develop from east to west; temporally, drought events exhibit high temporal overlap, and long-duration droughts often display multi-peak characteristics. Furthermore, drought events with extensive coverage and high severity were concentrated during 2005–2010. The conclusions of this study contribute to understanding the spatiotemporal evolution patterns of drought events in China and provide scientific references for drought monitoring and risk management.

## Full Text

# Characterization of the Evolution of Drought Events in China Based on 3D Identification

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**Abstract:** China is one of the countries most severely affected by drought worldwide, with frequent drought events causing serious impacts on economic and social development as well as ecological environments. Drought is inherently a spatiotemporal phenomenon that evolves across both space and time. This study combines a three-dimensional clustering algorithm to identify drought events in China from 1981 to 2020 and quantitatively analyze their spatiotemporal dynamic evolution processes from the fundamental perspective of spatiotemporal linkage. The main conclusions are as follows: The three-dimensional clustering algorithm can effectively identify drought events and their dynamic changes. From 1981 to 2020, China experienced 102 drought events lasting two months or more. Spatially, drought event trajectories tend to develop from east to west; temporally, drought events exhibit high temporal overlap, with long-duration droughts often showing multi-peak characteristics. Additionally, drought events with wide coverage and high severity were concentrated between 2005 and 2010. These findings help reveal the spatiotemporal evolution patterns of drought events in China and provide scientific references for drought monitoring and risk management.

**Keywords:** three-dimensional clustering algorithm; drought event; three-dimensional evolutionary features; dynamic evolution; SPEI; China

## Introduction

Drought is an anomalous meteorological and hydrological phenomenon, with each occurrence referred to as a drought event. Deepening our understanding of drought patterns requires accurate identification and extraction of drought events followed by multi-feature analysis. A drought event is essentially a spatiotemporally linked process that evolves in both temporal and spatial dimensions. Traditional drought identification methods are diverse, including threshold level methods, run theory, wavelet transforms, and empirical orthogonal functions. Numerous scholars have conducted drought monitoring research based on these methods, providing important references for drought event identification and quantitative feature analysis. For example, Ren et al. [**?**] analyzed extreme climate change trends in the arid region of Northwest China based on percentile threshold methods; Li et al. [**?**] applied run theory and Copula functions jointly to provide references for regional drought risk assessment; and Huang et al. [**?**] studied the correlation between hydrological and meteorological droughts in the Wei River Basin using cross-wavelet analysis methods. Empirical Orthogonal Function (EOF) and Rotated Empirical Orthogonal Function (REOF) have also been widely applied in spatiotemporal feature analysis of meteorological elements [**?**, **?**].

However, these methods are limited to one-dimensional or two-dimensional perspectives, typically simplifying the three-dimensional structure of drought events by compressing them into two or one dimension. Examples include temporal variation of drought indices in fixed regions (one-dimensional) or spatial distribution maps of dry/wet conditions during specific periods (two-dimensional). Drought events are fundamentally three-dimensional phenomena of dry/wet anomalies that develop in space and change over time. While dimensionality reduction enables more rapid extraction and analysis of drought events, it simultaneously destroys their three-dimensional spatiotemporal structure, leading to loss of critical information such as drought paths, development processes, and movement directions.

To address these issues, scholars have recently focused on three-dimensional perspectives for drought event identification and quantitative characterization, achieving certain progress. Andreadis et al. [?] used clustering algorithms to identify drought events and their spatial extents, establishing Severity-Area-Duration (SAD) curves to link drought area with severity. Lloyd-Hughes [?] proposed a three-dimensional drought identification method that clarifies the three-dimensional (longitude, latitude, time) structure of drought events by identifying drought pixels within a three-dimensional drought index cube. Later, Liu et al. [?] improved traditional three-dimensional clustering algorithms by measuring drought events through multiple variables including duration, severity, intensity, and centroid to analyze spatiotemporal evolution characteristics of drought events in Central Asia. Wen et al. [?] constructed three-dimensional threshold isosurfaces by clustering spatiotemporal grid points to form three-dimensional drought structures, characterizing spatiotemporal distribution patterns and variability during drought development. Xu et al. [?] identified drought events in China' s monsoon region from 1961 to 2012 using three-dimensional clustering methods, measuring events through duration, affected area, severity, intensity, and centroid. Feng et al. [?] analyzed spatiotemporal continuous dynamic evolution characteristics of drought in the Heihe River Basin using three-dimensional drought identification methods. Deng et al. [?] applied image three-dimensional connectivity identification methods to meteorological drought events in the Yangtze River Basin.

Under climate change and intensifying human activities, drought events in China are occurring more frequently with a trend toward further intensification, and their spatiotemporal characteristics are becoming increasingly complex. However, the spatiotemporal evolution patterns of drought events in China remain unclear, and understanding of drought occurrence and development processes still needs deepening. Therefore, this study identifies drought events in China from 1981 to 2020 based on a three-dimensional clustering algorithm from a spatiotemporal linkage perspective. Building upon analysis of conventional static features such as drought occurrence time, duration, severity, and intensity, this study quantitatively investigates dynamic evolution characteristics including development processes and movement paths. The aim is to deepen understanding of spatiotemporal evolution patterns of drought events, promote the development of drought identification and quantitative characterization, and provide scientific references for drought risk management and prediction.

### 1.1 Study Area Overview

China is located in eastern Asia on the west coast of the Pacific Ocean, with geographic coordinates between 73°33 -135°05 E and 3°51 -53°33 N (excluding Taiwan). The terrain is high in the west and low in the east, distributed in a stepwise pattern with large elevation differences. China is dominated by monsoon climate, spanning wide latitudes with strong spatial heterogeneity in solar radiation energy. Due to differences in thermal properties between land and sea, precipitation gradually decreases from southeast to northwest. Annual precipitation in southeastern coastal areas exceeds 1600 mm, decreases to about 800 mm at the Qinling-Huaihe line, reduces to 400 mm in the Greater Khingan Mountains area, further decreases to 200 mm in the western regions, and falls below 50 mm in the Tarim Basin. Drought and flood disasters show gradual changes, distributed nationwide, with disasters becoming more diverse from north to south. Drought is the main disaster type in northern China, while flooding is the most important disaster type in southern China [?]. Over the past half-century, extreme weather and climate events such as high temperatures and heavy precipitation have become more frequent and intense [?], and drought disasters have occurred frequently even in regions normally considered humid [?]. Drought events are typically concentrated in the North China Plain to the lower Yangtze River region, with obvious drought trends in the western North China Plain, Loess Plateau, Sichuan Basin, and Yunnan-Guizhou Plateau [?]. Frequent droughts have caused severe losses; for example, the rare major drought event in the Yangtze River Basin in summer 2022 caused serious impacts on local industrial and agricultural production, residents' lives, and ecological security [?, ?, ?].

#### 1.2.1 China Daily Precipitation Analysis Product

The China Daily Precipitation Analysis Product (CPAP) is obtained from the China Meteorological Data Network (data.cma.cn), produced by the National Meteorological Information Center with a spatial resolution of 0.25°$×$0.25°. [Figure 1: see original paper] shows the distribution of meteorological stations used to generate CPAP across China. All meteorological data undergo three-level quality control including extreme value testing, internal consistency testing, and spatial consistency testing [?]. Verified studies show good consistency between CPAP daily precipitation data and independent standardized observations across different regions of China, with a relative deviation of 3.21% at the monthly scale [?]. This study accumulates daily precipitation data to the monthly scale for drought index calculation.

ERA5-Land is a new high-resolution climate reanalysis grid dataset produced by the European Centre for Medium-Range Weather Forecasts, with a spatial resolution of 0.1°$×$0.1° [?]. The dataset includes monthly dynamic data for 50 variables characterizing temperature, lakes, snow cover, soil moisture, radiation and heat, evapotranspiration and runoff, wind speed, air pressure, precipitation, and vegetation since 1981, with long time series, high spatiotemporal resolution, and rich variables. ERA5-Land has been widely applied in weather and climate diagnosis, remote sensing data assimilation, and drought monitoring [?, ?]. ERA5-Land provides hourly and monthly versions [?]. This study downloaded monthly evapotranspiration (PET) grid data from its official website (https://cds.climate.copernicus.eu/) for drought index calculation.

## 2.2 Drought Event Identification Method Based on Three-Dimensional Clustering Algorithm

This study selects SPEI3<-1 as the identification standard for drought status. Following the improved three-dimensional clustering drought event identification method from Xu et al. [?], drought events are identified and their spatiotemporal evolution characteristics are quantitatively described. The specific steps are as follows:

1) **Construct three-dimensional data space.** Using historical monthly SPEI3 data for the study area as the basic data, with longitude (X), latitude (Y), and time (T) as the three coordinate axes (as shown in [Figure 2: see original paper]), a three-dimensional data space of SPEI3 is constructed. At this point, the size of this three-dimensional space is Nlat×Nlon×Nt, where Nlat, Nlon, and Nt represent the number of latitude grids, longitude grids, and time range (months) in the SPEI3 data space, respectively. The time range is set to 1981–2020.

2) **Drought patch identification.** For each month, drought status identification is performed on the SPEI3 data. When a grid point' s SPEI3<-1, it is considered to be in drought status and marked as a drought grid. Then, all drought grids in the current month are identified, and adjacent drought grids are marked as one drought patch.

3) **Drought patch screening.** In actual drought event analysis, droughts with wide coverage and long duration are the focus of research. Drought fragments have limited impact and can disturb drought event identification. To avoid the influence of drought fragments on identification and quantitative analysis [?], this study only considers drought patches with areas larger than 6400 $km^2$ (2 grid cells) [?].

4) **Drought event identification.** A three-dimensional drought event is a cluster of interconnected drought voxels in the three-dimensional drought index space. To determine a drought event, the overlapping area of drought patches from adjacent time periods must be defined. According to Lloyd-Hughes [?], when the overlapping area of drought patches in two adjacent layers exceeds 50%, they are identified as the same drought event. Starting from the second month, overlapping areas between drought patches in adjacent months are calculated month by

month until all monthly layers have been examined. Drought voxels are then extracted and assigned a unique identifier, representing one three-dimensional drought event.

## 2.3 Drought Event Characteristic Variables

This study measures drought events based on the following five drought characteristics:

1) **Drought Duration (DD):** The length of time in a drought state, i.e., the number of months between drought start time and drought end time.
2) **Drought Severity (DS):** The absolute value of the cumulative SPEI during the drought event period, calculated as:

$$DS = \sum_{i=1}^{DD} |SPEI_i|$$

   where DD represents the duration of a drought event, and SPEI_i represents the SPEI value in month i.

3) **Drought Intensity (DI):** The average value of |SPEI| during the drought event period, calculated as the ratio of drought severity to duration:

$$DI = \frac{\sum_{i=1}^{DD} |SPEI_i|}{DD} = \frac{DS}{DD}$$

   where DS represents drought severity, DD represents drought duration, and SPEI_i represents the SPEI value in month i.

4) **Drought Area (DA):** Also called drought spatial extent or drought influenced area, referring to the maximum area covered by a drought event, i.e., the maximum area that has been in drought status during the event period.
5) **Drought Centroids:** The weighted center of SPEI values in three-dimensional space, which is important for studying drought spatiotemporal dynamic evolution processes.

## 3.1 Drought Identification Results Based on Three-Dimensional Clustering Algorithm

Using SPEI3 and the three-dimensional clustering algorithm drought identification method, 102 drought events lasting two months or more were identified in mainland China from 1981 to 2020. lists the spatiotemporal characteristics of these 102 drought events, quantitatively describing each event's occurrence time, end time, severity, impact range, centroid, and centroid path length. Statistics show that among the 102 drought events, 12.7% lasted longer than 12 months, and 10.8% covered areas exceeding 4.80$×10^{5}$ km$^2$ (5% of China' s land area). Meanwhile, the severity of drought events lasting more than 12 months all ranked in the top 10% of all drought events, indicating that drought duration is an important factor leading to drought severity. In summary, drought events in China over the past 40 years show temporal continuity and spatial universality.

## 3.2 Analysis of Drought Characteristic Changes

[Figure 3: see original paper] shows the spatial distribution of centroids for the 102 drought events, where circle size and color represent drought severity and duration, respectively. Drought event centroids are uniformly distributed across the study area, while long-duration, high-intensity, large-scale drought events are mainly concentrated in central China regions such as Qinghai, Gansu, and Inner Mongolia. This "central region effect" is primarily caused by boundary limitations of the study area [?]. Large-scale drought events are more concentrated in southern regions.

To characterize drought event development and migration processes, monthly drought centroids are calculated. Based on the movement direction of drought centroids, [Figure 4: see original paper] presents a stacked column chart and rose diagram of drought event duration and movement direction in China from 1981 to 2020, with different colors indicating drought duration. The results show that droughts in China tend to develop from east to west. No obvious pattern exists for drought duration across different directions. Among the eight directions (east, west, south, north, northeast, northwest, southeast, southwest), the cumulative number of drought events is highest in the west, reaching 36 events (35.3% of total drought occurrences). Drought events in the northwest, west, and southwest directions total 64 events, accounting for 62.7% of total occurrences, including 25 northwestward and 23 southwestward events. Drought events in other directions are relatively weaker, with 9, 6, 5, 4, and 4 events in the east, northeast, north, south, and southeast directions, respectively.

Based on monthly drought severity, monthly drought area, and monthly drought intensity for each drought event, [Figure 5: see original paper] shows the temporal evolution of these characteristics, with different colors marking different drought durations and rectangles representing the impact area of individual drought events. As shown, drought events have high temporal overlap, with many simultaneous drought events occurring in different regions. From the perspective of long-term sequence distribution density, drought events with wide coverage and high severity occurred more frequently between 2005 and 2010. Drought severity shows high correlation with drought area, but intensity shows weak correlation with duration and severity. This indicates that wider drought coverage is more likely to trigger high-severity drought events. For example, the drought event from June 2007 to May 2008 covered 53.7% of the study area, characterized by large affected area and severe local damage [?], making it the most severe drought event in the study period. Based on temporal evolution of drought area, severity, and intensity ([Figure 5: see original paper]), approximately 57.84% of the 102 drought events showed multi-peak phenomena in drought area and severity, meaning that during a single drought event, changes in drought area and severity exhibit multiple peaks. Over half (57.84%) of drought events show multi-peak phenomena in drought intensity changes. This multi-peak phenomenon complicates drought event development prediction, as a transition from increase to decrease in certain drought characteristics (intensity, severity, area) does not necessarily indicate drought termination and may be followed by new upward trends.

Affected by climate change, three-dimensional drought characteristics in China show complex variations. [Figure 6: see original paper] shows cumulative frequency, mean duration, mean intensity, mean severity, and mean area of drought events by decade. Over the past 40 years, the average duration of single drought events shows an obvious upward trend. Mean drought intensity remains stable at approximately 1.4. Mean drought duration, severity, and area show similar trends, first increasing then slightly decreasing. Overall, long-duration drought events increased significantly after 2000, with 13 such events occurring between 2001-2020, averaging 15.2 months in duration and 2.8$×10^{5}$ km$^2$ in area. The longest drought event in the past 40 years lasted 26 months. In long-duration drought events, characteristics such as severity and area often produce multiple peaks, which is unfavorable for predicting drought development processes.

## 3.3 Analysis of Typical Three-Dimensional Drought Events

To analyze spatial patterns and temporal evolution characteristics of typical drought events, this study selected five typical drought events from the 102 identified events based on different three-dimensional drought characteristic values: the most severe, highest intensity, longest duration, shortest duration, and high intensity with relatively short duration under equivalent severity. These are marked with light yellow backgrounds in . [Figure 7: see original paper] shows the three-dimensional structures and temporal trends of characteristic variables for typical drought events. [Figure 8: see original paper] shows temporal changes of characteristic variables for typical drought events.

As seen in [Figure 8: see original paper], within a single drought event, monthly changes in drought severity, drought area, and drought intensity show consistent trends. Drought Event 1 (June 2007–May 2008) has the same duration as Drought Event 2 but much lower severity, primarily due to differences in drought area. Drought Event 1 gradually developed westward from northeastern China, with relatively concentrated drought-affected areas, while Drought Event 2 spread from the intersection of Shaanxi, Shanxi, and Inner Mongolia to the entire country, with high drought intensity and wide impact area, covering 8.00$×10^{5}$ km$^2$ (8.3% of China' s land area) over 12 months. The drought event reached its peak coverage in August 2007, exceeding 5.00$×10^{5}$ km$^2$. Previous research verified the autumn-winter drought phenomenon in northern China from October 2007 to January 2008 [?], with described drought impacts consistent with the drought area identified in this study. This shows that under the same drought duration, drought coverage area plays a decisive role in drought severity.

Drought Event 3 (March–October 1999) occurred in northeastern China. Despite having the same severity as Drought Event 1 (both $1.74\times10^{5}$), its drought intensity was higher than Drought Event 1, indicating that under equivalent severity, smaller drought intensity corresponds to larger drought area, and vice versa. Drought Event 4, the highest intensity drought event, had relatively short duration compared to other events with equivalent severity, indicating this drought event was brief but intense. Drought Event 5, the shortest duration event (2 months), ranked 7th in intensity among all identified drought events. Compared to drought events with equivalent severity, this event was short and intense, consistent with the characteristics of Drought Event 4.

To analyze the entire spatiotemporal dynamic evolution process and monthly migration paths of typical drought events, [Figure 9: see original paper] maps the evolution from drought occurrence to extinction for the June 2007–May 2008 drought event, with points representing monthly drought cluster centroids and arrows connecting centroids showing drought migration paths. The drought originated in northern Inner Mongolia, with its centroid in Chifeng City when the drought began. The drought then rapidly spread to the entire northeastern region, with the centroid moving northeast to Baicheng City. In August 2007, the drought continued developing northward, with increasing severity reaching its most serious stage, with monthly drought area of $1.38\times10^{6}$ km$^2$. In September 2007, the drought dispersed into two parts, and the centroid moved westward to Qiqihar City. In October 2007, the drought center gradually moved eastward, and the drought began to attenuate. In November 2007, the drought center continued moving northward, eventually reaching northern Hulunbuir City where it finally dissipated. Overall, this drought event lasted 12 months, with a short growth period (2 months) and longer attenuation period (4 months), experiencing three stages: growth, maturity, and attenuation. The drought centroid moved from south to north along the path: Chifeng City → Baicheng City → Qiqihar City → southern Hulunbuir City → northern Hulunbuir City. This drought event shows high consistency with the spring and autumn droughts in 2007–2008 documented in the Atlas of China' s Meteorological Drought [?], further validating the reliability of the three-dimensional clustering algorithm for drought identification.

## 4 Conclusions and Discussion

This study identifies drought events in China from 1981 to 2020 from a three-dimensional perspective and systematically analyzes basic characteristics including duration, severity, intensity, and impact area, as well as dynamic features such as movement paths and development directions. The three-dimensional clustering algorithm provides a new approach for revealing spatiotemporal variation patterns of drought, and the conclusions help deepen understanding of drought event occurrence and development processes in China. The main conclusions are as follows:

The three-dimensional clustering algorithm can effectively identify regional meteorological drought events. A total of 102 drought events lasting more than 2 months were identified in China from 1981 to 2020. The most severe drought event occurred from June 2007 to May 2008, lasting 12 months and affecting over 8% of China' s land area. Different drought events show significant differences in spatiotemporal characteristics, and monthly variations in intensity and severity within the same drought event are also quite distinct.

Analysis of drought centroid distribution, duration charts, and movement direction rose diagrams reveals that long-duration, high-intensity, large-scale drought events in China mainly concentrate in central and western regions, with 62.7% of drought events tending to develop from east to west. Through monthly analysis of characteristic changes, drought events in China show high temporal overlap. From long-term sequence distribution density, drought events with wide coverage and high severity occurred more frequently between 2005 and 2010. Among the 102 drought events, approximately 57.84% showed multi-peak phenomena in drought area and severity, and over half (57.84%) showed multi-peak phenomena in drought intensity changes. This multi-peak phenomenon complicates prediction of drought event development.

Comparative analysis with historical literature shows that the three-dimensional clustering algorithm is reasonable and reliable. Each typical drought event' s occurrence time and impact range show high consistency with documented records.

This study has several limitations. First, the SPEI index is calculated based on precipitation and potential evapotranspiration, essentially reflecting meteorological drought [?] without considering underlying surface factors such as vegetation type and terrain. Second, while some studies [?] indicate that using area proportions of the study region as minimum drought cluster area thresholds can effectively extract three-dimensional drought events and avoid fragmentation, different threshold sizes lead to differences in extraction results, and the rationality of threshold selection requires further validation. Finally, although the three-dimensional clustering drought identification algorithm can effectively avoid loss of dynamic drought information [?], it faces relatively complex computational challenges.

## References

[1] IPCC. Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the intergovernmental panel on climate change[J]. Journal of Clinical Endocrinology & Metabolism, 2012, 18(6): 586-599.

[2] Zhang X, Chen N, Sheng H, et al. Urban drought challenge to 2030 sus-

tainable development goals[J]. Science of the Total Environment, 2019, 693: 133536-133547.

[3] Su B, Huang J, Fischer T, et al. Drought losses in China might double between the 1.5 degrees C and 2.0 degrees C warming[J]. Proceedings of the National Academy of Sciences of The United States of America, 2018, 115(42): 10600-10605.

[4] Zhang Q, Yao Y, Li Y, et al. Progress and prospect on the study of causes and variation regularity of droughts in China[J]. Acta Meteorologica Sinica, 2020, 78(3): 500-521.

[5] Guo H, Bao A, Ndayisaba F, et al. Space time characterization of drought events and their impacts on vegetation in Central Asia[J]. Journal of Hydrology, 2018, 564: 1165-1178.

[6] Ren Z, Yang D. Study on trends of extreme climate change in the arid region of Northwest China in resent 40 years[J]. Journal of Arid Land Resources and Environment, 2007, 21(4): 10-13.

[7] Li T, Wang S, Zhuang W, et al. Application of the theory of run and Copula function to the joint distribution of two dimension drought variables[J]. Journal of Arid Land Resources and Environment, 2016, 30(6): 77-82.

[8] Huang S, Li P, Huang Q, et al. The propagation from meteorological to hydrological drought and its potential influence factors[J]. Journal of Hydrology, 2017, 547: 184-195.

[9] Tatli H, Türkeş M. Empirical orthogonal function analysis of the palmer drought indices[J]. Agricultural and Forest Meteorology, 2011, 151(7): 981-991.

[10] Zhu Y. The regional division of dryness/wetness over Eastern China and variations of dryness/wetness in northern China during the last 530 years[J]. Acta Geographica Sinica, 2003, 58(S1): 100-107.

[11] Andreadis K M, Clark E A, Wood A W, et al. Twentieth century drought in the conterminous United States[J]. Journal of Hydrometeorology, 2005, 6(6): 985-1001.

[12] Lloyd Hughes B. A spatio temporal structure based approach to drought characterisation[J]. International Journal of Climatology, 2012, 32(3): 406-418.

[13] Liu Y, Zhu Y, Ren L, et al. Understanding the spatiotemporal links between meteorological and hydrological droughts from a Three Dimensional Perspective[J]. Journal of Geophysical Research: Atmospheres, 2019, 124(6): 3090-3109.

[14] Wen X, Tu Y, Tan Q, et al. Construction of 3D drought structures of meteorological drought events and their spatio temporal evolution characteristics[J]. Journal of Hydrology, 2020, 590(6): 125539-125550.

[15] Xu K, Yang D, Yang H, et al. Spatio temporal variation of drought in China during 1961-2012: A climatic perspective[J]. Journal of Hydrology, 2015, 526: 253-264.

[16] Feng K, Su X. Spatiotemporal response characteristics of agricultural drought to meteorological drought from a three dimensional perspective[J]. Transactions of the Chinese Society of Agricultural Engineering, 2020, 36(8): 103-113.

[17] Deng C, She D, Zhang L, et al. Multi characteristic analysis of drought events in the Yangtze River Basin based on image three dimensional connectivity identification method[J]. Transactions of the Chinese Society of Agricultural Engineering, 2021, 37(11): 131-139.

[18] Du X, Jin X, Yang X, et al. Spatial temporal pattern changes of main agriculture natural disasters in China during 1990- 2011[J]. Journal of Geographical Sciences, 2015, 25(4): 387-398.

[19] Wang R, Li X, Zhou R, et al. Applicability analysis of three meteorological drought indices in Sichuan Province[J]. Resources and Environment in the Yangtze Basin, 2021, 30(3): 734-744.

[20] Zhai J, Su B, Krysanova V, et al. Spatial variation and trends in PDSI and SPI indices and their relation to streamflow in 10 large regions of China[J]. Journal of Climate, 2010, 23(3): 649-663.

[21] Hao L, Ma N, He L. Circulation anomalies characteritics of the abnormal drought and high temperature event in the middle and lower reaches of the Yangtze River in summer of 2022[J]. Journal of Arid Meteorology, 2022, 40(5): 721-732.

[22] Li Y, Zhang J, Yue P, et al. Study on characteristics of severe drought event over Yangtze River Basin in summer of 2022 and its causes[J]. Journal of Arid Meteorology, 2022, 40(5): 733-747.

[23] Zhang Q. Scientific interpretation of severe drought in the Yangtze River Basin[J]. Journal of Arid Meteorology, 2022, 40(4): 545-548.

[24] Shen Y, Feng M, Zhang H, et al. Interpolation methods of China daily precipitation data[J]. Journal of Applied Meteorological Science, 2010, 21(3): 279-286.

[25] Shen Y, Xiong A. Validation and comparison of a new gauge based precipitation analysis over mainland China[J]. International Journal of Climatology, 2016, 36(1): 252-265.

[26] Muñoz Sabater J, Dutra E, Agustí-Panareda A, et al. ERA5-Land: A state of the art global reanalysis dataset for land applications[J]. Earth System Science Data, 2021, 13(9): 4349-4383.

[27] Zandler H, Senftl T, Vanselow K A. Reanalysis datasets outperform other

gridded climate products in vegetation change analysis in peripheral conservation areas of Central Asia[J]. Scientific Reports, 2020, 10(1): 22446.

[28] Xue C, Wu H, Jiang X. Temporal and spatial change monitoring of drought grade based on ERA5 analysis data and BFAST method in the Belt and Road area during 1989-2017[J]. Advances in Meteorology, 2019, 2019: 4053718-4053729.

[29] Chen H, Sun J. Changes in drought characteristics over China using the standardized precipitation evapotranspiration index[J]. Journal of Climate, 2015, 28(13): 5430-5449.

[30] Zhou Y, Li N, Ji Z, et al. Temporal and spatial patterns of droughts based on Standard Precipitation Index (SPI) in Inner Mongolia during 1981-2010[J]. Journal of Natural Resources, 2013, 28(10): 1694-1706.

[31] Wang A, Lettenmaier D P, Sheffield J. Soil moisture drought in China, 1950-2006[J]. Journal of Climate, 2011, 24(13): 3257-3271.

[32] Vicente-Serrano S M, Beguería S, López-Moreno J I. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index[J]. Journal of Climate, 2010, 23(7): 1696-1718.

[33] Wang J. Study on spatiotemporal characteristics of drought in Xinjiang based on Multi Source Weighted Ensemble Precipitation product[J]. Arid Zone Research, 2022, 39(5): 1398-1409.

[34] Guo H, Bao A, Liu T, et al. Meteorological drought analysis in the lower Mekong Basin using satellite based long term CHIRPS product[J]. Sustainability, 2017, 9(6): 1-21.

[35] Ma B, Zhang B, Jia L, et al. Conditional distribution selection for daily MSWEP and its revealed meteorological drought characteristics in China from 1961 to 2017[J]. Atmospheric Research, 2020, 246: 105128.

[36] Guo H, Bao A, Liu T, et al. Spatial and temporal characteristics of droughts in Central Asia during 1966-2015[J]. Science of the Total Environment, 2018, 624: 1523-1538.

[37] Diaz V, Corzo-Perez G A, Van Lanen H A J, et al. Characterisation of the dynamics of past droughts[J]. Science of the Total Environment, 2020, 718: 134588.

[38] Colwell R K, Lees D C. The mid domain effect: Geometric constraints on the geography of species richness[J]. Trends in Ecology & Evolution, 2000, 15(2): 70-76.

[39] Feng L. National drought and drought action in 2009[J]. China Flood & Drought Management, 2010, 20(1): 76-79.

[40] Wang H, Bai A. The severe drought in eastern China by the anomalies atmospheric circulation in winter 2008[J]. Journal of Arid Land Resources and

Environment, 2010, 24(11): 104-109.

[41] Jiang D, Fu J, Jingying, Zhuang D, et al. Dynamic drought remote sensing monitoring in North China from 2008 to 2009[J]. Journal of Natural Disasters, 2012, 21(3): 92-101.

[42] Compilation group of China Flood and Drought Disaster Prevention Bulletin. Summary of China Flood and Drought Disaster Prevention Bulletin 2020[J]. China Flood & Drought Management, 2021, 31(11): 7.

[43] China Meteorological Administration. Atlas of China' s Meteorological Drought[M]. Beijing: Meteorological Press, 2010.

[44] Feng K, Li Y, Wang F, et al. Analysis of drought events in Northwest China based on an improved three dimensional identification method[J]. Water Resources Protection, 2023, 39(1): 63-72.

*Note: Figure translations are in progress. See original paper for figures.*