Multidimensional Copula-Based Analysis of Drought Characteristics and Hazard in China: Postprint

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Abstract

Drought constitutes one of the primary natural disasters in China. Conducting a nationwide characteristic analysis of drought and evaluating drought occurrence probabilities facilitates a macroscopic comprehension of China' s overall drought risk pattern and holds significant implications for drought monitoring and early warning endeavors. Based on the daily surface climate dataset from the National Meteorological Information Center spanning 1980–2019, the Standardized Precipitation Evapotranspiration Index (SPEI) was computed, historical drought events were identified via run theory, extracting three characteristic variables of drought duration, drought severity, and peak intensity, and Copula functions were utilized to analyze the occurrence probabilities and return periods of various drought event types across China. The results demonstrate that: from the perspective of drought severity, China is most susceptible to "mild drought" and "moderate drought" ; regarding drought duration, China is most prone to "cross-seasonal" drought, with the northern arid region exhibiting the highest susceptibility to "over-half-year" drought compared to other agricultural zones. The occurrence probability of "high peak intensity" drought is substantially lower than that of "low peak intensity" drought, with its probability increasing as drought duration extends. The joint return periods for various types of "high peak intensity" drought in the Huang-Huai-Hai Plain, the middle and lower reaches of the Yangtze River, and South China are generally short.

Full Text

Drought Characteristics and Risk Hazard in China Based on Multidimensional Copula Model

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Abstract

Drought is one of the most serious natural disasters that human society is facing, which substantially affects agriculture and animal husbandry. China is a region with high incidents of drought disasters globally. For drought monitoring, early warning and ecological environment protection in China, analyzing the characteristics of drought and assessing its occurrence probability is crucial. The standardized precipitation-evapotranspiration index (SPEI) series at 1-, 3-, 6-, and 12-month timescales were calculated using the daily surface climate data set of the National Meteorological Data Center from 1980 to 2019. After comparing and analyzing the fluctuations in the SPEI series at different timescales, the 3-month-timescale SPEI (SPEI-3) was selected to identify historical drought events and extract three characteristic variables (drought duration, drought severity, and intensity peak) based on the theory of runs. SPEI-3 can fully reflect the seasonal dryness and humidity and is commonly used in agricultural drought monitoring. Then, using two- and three-dimensional Copula models, the joint distribution between two- and three-dimensional drought characteristic variables was constructed to estimate the occurrence probabilities of drought events under different combinations of drought duration and drought severity and those under different combinations of drought duration, drought severity, and intensity peak, respectively. Finally, the return periods of a single drought characteristic variable and the joint return periods of different types of "high-intensity-peak drought" were calculated. The results show that "mild drought" and "moderate drought" are most likely to occur in China from the perspective of drought severity. In terms of drought duration, "cross-season drought" is most likely to occur in China, and "drought over half a year" is most likely to occur in the northern arid region compared with other agricultural regions. The occurrence probability of "high-intensity-peak drought" is much less than that of "low-intensity-peak drought" , and its probability increases with increasing drought duration. The joint return periods of "high-intensity-peak drought" in the North China Plain, middle and lower Yangtze River Plain, and southern China are generally shorter than those in other regions. Short duration ("monthly drought" , "intra-season drought" , and "cross-season drought") and low severity ("mild drought" and "moderate drought") are the dominant factors for the joint return periods of various drought events in China. In this study, multidimensional drought characteristic analysis and hazard assessment were conducted nationwide, which are conducive for macroscopic understanding of the overall drought risk pattern in China and provide reference for drought

control and prevention.

Keywords: drought; hazard; return period; Copula

1. Introduction

Drought generally refers to a persistent state of water deficit, though specific definitions vary depending on disciplinary perspectives and drought types, such as meteorological drought (insufficient precipitation), hydrological drought (insufficient surface or groundwater flow), agricultural drought (insufficient soil moisture), and socioeconomic drought (depletion of water resource demand). As a complex and quasi-periodic climate phenomenon, drought negatively impacts agriculture, water resources, and ecological environments, thereby affecting economic development and social stability. In the context of global climate change, extreme drought (or extreme precipitation) events have become increasingly frequent, particularly after 2010 when the global drought area increased significantly. Studies have shown that during 1950-2008, the proportion of global drought areas increased at a rate of 1.74% per decade. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), rising surface temperatures and intensified evaporation from underlying surfaces will remain important manifestations of future global warming, which may increase the frequency of extreme weather events including drought.

China is located in the East Asian monsoon region with high precipitation variability and frequent drought disasters. Numerous scholars have conducted research on drought characteristics in China. Traditional drought studies have primarily characterized drought events based on frequency analysis. However, drought occurrence is actually related to multiple variables, and its characteristics can be manifested in various ways. Single drought variables are insufficient to represent complex drought conditions and their impacts. Consequently, drought characteristic analysis has gradually expanded from a single dimension to multiple dimensions. Copula functions can establish joint distributions of multiple drought characteristic variables, integrating independent multidimensional drought characteristics into a unified drought event framework to estimate the occurrence probabilities of different types of drought events, thereby advancing the understanding of drought event development processes and prediction.

The Copula method has been widely applied in drought characteristic research in China, but two main deficiencies remain. First, current studies are mostly based on site scales or local regions (such as Xilingol, Beijing-Tianjin-Hebei region, etc.). While such studies can provide accurate information for small-scale drought risk management, they cannot meet the needs of large-scale drought management and risk assessment. Second, current research mostly focuses on the joint distribution of two-dimensional variables (drought severity and drought duration), with relatively few studies on three-dimensional or higher-dimensional drought variables.

In summary, this study uses monthly climate data from meteorological stations across China to calculate and analyze the fluctuations of the Standardized Precipitation Evapotranspiration Index (SPEI) at different timescales. The 3-month timescale SPEI (SPEI-3), which can fully reflect seasonal dry-wet changes and is commonly used in agricultural drought monitoring, was selected for drought identification. Based on three drought characteristic variables (drought severity, drought duration, and intensity peak), this study analyzes the three-dimensional joint distribution and return periods of drought characteristics in different agricultural regions of China. This research is of great theoretical significance for comprehensively understanding the overall drought pattern in China, strengthening precise drought monitoring, improving the reliability of risk assessment, and assisting in short-term and long-term strategic planning for water resource management.

2. Study Area and Data

2.1 Study Area

The study area is mainland China (Figure 1). Following the principle of provincial administrative unit integrity and based on agricultural production conditions, characteristics, and development directions, the map details the regional distribution and zonal differentiation of China' s nine major agricultural zones. Using the arid region boundary map from previous studies on dryland drought in northern China, which subdivides the entire arid region into extreme arid, arid, semi-arid, and sub-humid arid zones according to the UN Millennium Ecosystem Assessment Report, the northern arid and semi-arid zones in China' s nine agricultural zoning map were further divided into northern arid region and northern semi-arid region, forming the final ten subregions used in this study (Figure 1).

[Figure 1: see original paper] Study area and distribution of the meteorological stations

2.2 Data Sources

The research data mainly include the daily surface climate dataset from the National Meteorological Data Center (http://data.cma.cn/data/cdcdetail/dataCode/SURF_{{{CLI}}*{{CHN}}*}} which provides daily meteorological data series including atmospheric pressure, temperature, precipitation, relative humidity, evaporation, wind direction and speed, and sunshine hours. After eliminating missing data, a total of 756 basic meteorological observation stations were selected. All selected stations have undergone strict quality checks and controls, including extreme value tests and temporal consistency tests, to eliminate the influence of non-climatic factors. The agricultural zoning map was obtained from the Data Sharing Center of the Institute of Geographic Sciences and Natural Resources, Chinese Academy of Sciences (http://www.resdc.cn/).

2.3 Methods

The technical route of this study is shown in Figure 2. The main components include: calculation of SPEI at different timescales, identification of drought events and extraction of drought variables, and analysis and return period analysis.

[Figure 2: see original paper] Technical flowchart

2.3.1 SPEI Calculation The Standardized Precipitation Evapotranspiration Index (SPEI) can capture the impact of temperature rise on water demand. Its multi-scale characteristics enable the identification of different drought types, which is of great significance for drought analysis and monitoring under global warming. This study calculated SPEI at 1-month (SPEI-1), 3-month (SPEI-3), 6-month (SPEI-6), and 12-month (SPEI-12) timescales. The calculation of potential evapotranspiration followed the Penman-Monteith formula recommended by the Food and Agriculture Organization (FAO).

2.3.2 Drought Event Identification This study used run theory to identify drought events. Run theory determines the start, duration, and end of drought events through the relationship between drought indices and thresholds. The three-threshold method has superior identification capability compared with the traditional single-threshold method. Referring to previous studies, the identification rules for drought events in this study were established as follows: (1) A drought is identified when the drought index falls below a threshold value; (2) If a drought event lasts only one month and the drought index is higher than a certain value, the event is eliminated; (3) If the time interval between two adjacent drought events is only one month, they are merged into one drought event; otherwise, the two drought events are considered independent.

After identifying drought events, the duration (the continuous period from the start to the end of a drought event), severity (the inverse of the mean negative run value during the drought event), and intensity peak (the inverse of the extreme negative run value) were calculated for each drought event. Referring to previous studies, the severity values for mild, moderate, severe, and extreme drought were defined as [0.5, 1), [1, 1.5), [1.5, 2), and [2, $+\infty$), respectively. The drought duration values for monthly, intra-seasonal, cross-seasonal, and over-half-year droughts were defined as (1, 3], (3, 6], (6, $+\infty$), respectively. The intensity peak values for low-intensity-peak and high-intensity-peak droughts were defined as ($-\infty$, 2) and [2, $+\infty$), respectively.

2.3.3 Copula Function Construction Copula functions construct joint distributions from known marginal distributions to analyze nonlinear correlations between variables. This study first used kernel density estimation to calculate the marginal distributions of each drought variable (drought duration, drought severity, and intensity peak) at each station. Then, two-dimensional (three-dimensional) normal Copula functions and Archimedean

Copula functions (Gumbel, Clayton, and Frank) were selected to construct the two-dimensional joint distribution between drought duration and drought severity, and the three-dimensional joint distribution among drought duration, drought severity, and intensity peak. Finally, the theoretical Copula functions were calculated. The Euclidean distance (D^2), Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC) were used to select the model with the smallest values of these indicators as the optimal model for analysis.

2.3.4 Drought Return Period Calculation The return period represents the occurrence cycle of meteorological disaster events. Assuming the marginal distribution functions of drought duration, drought severity, and intensity peak are u, v, and w, respectively, the return period calculation formulas for drought duration (D, in months), drought severity (S), and intensity peak (I) are:

$$T_D = \frac{N}{n \cdot P(D \geq d)}$$

$$T_S = \frac{N}{n \cdot P(S \geq s)}$$

$$T_I = \frac{N}{n \cdot P(I \geq i)}$$

where T_D, T_S, and T_I are the return periods of drought duration, drought severity, and intensity peak, respectively; n is the number of drought occurrences; and N is the sequence length.

The joint return period (T_α) for drought duration, drought severity, and intensity peak greater than or equal to specific values is calculated as:

$$T_\alpha = \frac{N}{n \cdot P(D \geq d, S \geq s, I \geq i)} = \frac{N}{n \cdot [1 - C(u, v, w)]}$$

where d, s, and i are the given drought duration, drought severity, and intensity peak, respectively; P is the joint probability of drought duration, drought severity, and intensity peak being greater than or equal to specific values; and $C(u, v, w)$ is the three-dimensional joint distribution function of drought duration, drought severity, and intensity peak.

It can be seen that the joint return period is calculated from any variable among D, S, and I being greater than or equal to a specific value. Therefore, the variable with the smallest return period under threshold conditions will be the dominant variable of the joint return period. Finally, inverse distance weighted interpolation was used to interpolate the calculated drought occurrence probabilities and return periods from the 756 stations to a 0.1°$×$0.1° grid to visually reflect spatial variations.

3. Results

3.1 Variations in Drought at Different Timescales

The SPEI values at different timescales fluctuate around zero over time (Figure 4). SPEI-1 shows intense fluctuations, reflecting monthly dry-wet changes and is generally used for comparing drought characteristics at different timescales. SPEI-3 reflects seasonal dry-wet changes and is commonly used for agricultural drought monitoring. SPEI-6 is relatively stable, representing interannual drought variations and is used for monitoring long-term drought. SPEI-12 shows the most stable pattern, representing multi-year drought characteristics. Previous studies have shown that vegetation responses in northwest China are generally high for SPEI-3. Overall, the smaller the timescale, the more intense the SPEI fluctuations; the larger the timescale, the smoother the dry-wet transitions. China' s precipitation is concentrated in summer and scarce in winter, and the seasonal variation of precipitation leads to significant seasonal drought characteristics in China, especially in southern regions. Therefore, SPEI-3 can fully reflect seasonal drought changes and was selected as the drought index for subsequent research.

[Figure 4: see original paper] Time series of standard evapotranspiration precipitation index (SPEI) with different time scale from 1980 to 2019

3.2 Hazard Probability Distribution Based on Two-Dimensional Drought Characteristics

The occurrence probabilities of drought events under different combinations of drought duration and drought severity (Figure 5) show that when drought duration is "monthly" or "intra-seasonal," "mild drought" is most likely to occur in China. The probability of "monthly mild drought" is between 10%-20% in most areas of the country, with only the western part of the northern arid region (R1) ranging between 1%-5%. The probability of "intra-seasonal mild drought" is between 5%-10% in most areas, with some regions exceeding 10%. When drought duration is "cross-seasonal" or "over half a year," "moderate drought" is the main drought type in China. The probability of "over-half-year moderate drought" in the northern arid region (R1) is between 20%-30%, with its western part showing significantly higher probabilities of "over-half-year mild drought" and "over-half-year moderate drought" than other regions. Overall, "cross-seasonal moderate drought" has the highest occurrence probability among all drought types, while "extreme drought" has generally low occurrence probability. From the perspective of drought duration, "cross-seasonal" drought is most likely to occur in China; from the perspective of drought severity, "mild drought" and "moderate drought" are most likely to occur.

[Figure 5: see original paper] Spatial distributions of probabilities under different drought types based on two dimensional drought characteristics

3.3 Hazard Probability Distribution Based on Three-Dimensional Drought Characteristics

Introducing the third drought characteristic (intensity peak) into the drought classification method helps further monitor intensity fluctuations within drought events. The occurrence probabilities of drought events under different combinations of drought duration, drought severity, and intensity peak (Figure 6 and Figure 7) show that under "low-intensity-peak" conditions (Figure 6), "mild drought" is most likely to occur when drought duration is "monthly" or "intra-seasonal," while "moderate drought" is the main drought type when drought duration is "cross-seasonal" or "over half a year." Under "high-intensity-peak" conditions (Figure 7), the probability of "cross-seasonal moderate drought" is relatively high across the country, while the occurrence probabilities of other drought types are all less than 5%. From a regional perspective, drought types in China's agricultural regions are dominated by "low-intensity-peak" drought. The highest probability is "intra-seasonal low-intensity-peak mild drought," followed by "cross-seasonal low-intensity-peak moderate drought." "High-intensity-peak" drought has the characteristic of long duration, generally occurring in "cross-seasonal" and "over-half-year" drought events, with the northern arid region (R1) having the highest probability of "over-half-year high-intensity-peak moderate drought."

[Figure 6: see original paper] Spatial distributions of probabilities of different drought types under a "low intensity peak"

[Figure 7: see original paper] Spatial distributions of probabilities of different drought types under a "high intensity peak"

3.4 Drought Return Period Analysis Based on Three-Dimensional Drought Characteristics

The joint return periods under different combinations of drought duration, drought severity, and intensity peak (Figure 8 and Figure 9) show that when drought duration is "monthly" and drought severity is "mild drought," the mean joint return periods of different types of "high-intensity-peak drought" range between 1.0-1.5 years, with the shortest periods in the North China Plain (R4), middle and lower Yangtze River region (R7), and southern China (R8). When drought duration is "cross-seasonal," the joint return periods for "severe drought" and "extreme drought" across the country are all greater than 1.5 years. When drought duration is "over half a year," the regions with the shortest joint return periods for "moderate drought," "severe drought," and "extreme drought" are southern China (R8), middle and lower Yangtze River region (R7), and North China Plain (R4), respectively. Overall, "monthly high-intensity-peak mild drought" has the shortest joint return period, while "over-half-year high-intensity-peak extreme drought" has the longest joint return period.

High-intensity-peak drought has a low occurrence probability but causes severe damage and has attracted widespread attention in the context of climate warming. The joint return periods of "high-intensity-peak drought" increase nonlinearly with increasing drought duration and severity, with longer durations (higher intensities) showing greater increases in joint return periods. By comparing the distributions of single-variable return periods (Figure 10), it is found that in drought events with "high-intensity-peak," "mild drought" has the shortest single-variable return period, and its return period distribution is similar to the joint return period distribution. In this case, drought severity is the dominant factor for the joint return period. Similarly, for "monthly," "intra-seasonal," and "cross-seasonal" droughts, drought duration is the dominant factor for the joint return period. For "over-half-year severe and extreme drought," the joint return period distribution differs significantly from the single-variable return period distributions, suggesting that drought duration, drought severity, and intensity peak all exert influence.

[Figure 8: see original paper] Boxplots of joint return period of different drought types under a "high intensity peak" in each agricultural region

[Figure 9: see original paper] Distributions of joint return period of different drought types under a "high intensity peak" in each agricultural region

[Figure 10: see original paper] Distributions of single return period in each agricultural region

4. Discussion

Traditional two-dimensional drought characteristic analysis ignores intensity fluctuations within drought events. This study introduces the intensity peak dimension, which strengthens the distinction of internal event characteristics while maintaining the integrity of drought events, providing new perspectives for drought characteristic research. Based on national agricultural zoning, this study analyzes the occurrence probabilities and return periods of different drought types, which helps distinguish drought characteristics across different agricultural regions in China and provides a good foundation and supplement for agricultural drought research. Future work could combine relevant agricultural data to further investigate the coupling relationship between crop water deficit and agricultural drought.

In drought event analysis, the selection of drought indices and determination of drought index thresholds are particularly important. This study did not further consider other timescales of SPEI or thresholds. Future research could combine the most suitable indices and thresholds for different regions based on regional divisions. Additionally, drought is a three-dimensional phenomenon that develops in both time and space. The center of drought and the scope of its affected area are also important characteristics of drought. Identifying drought intensity centers and drought intensity cluster areas, and studying the spatiotemporal changes of drought centers and affected areas, are also important directions for future research.

5. Conclusions

1) "Cross-seasonal moderate drought" is most likely to occur overall in China. The northern arid region is more prone to "over-half-year" drought than other agricultural regions.
2) The occurrence probability of "high-intensity-peak drought" is much smaller than that of "low-intensity-peak drought," and its probability increases with increasing drought duration.
3) The joint return periods of "high-intensity-peak drought" in all agricultural regions increase with increasing drought duration and severity. The joint return periods are generally shorter in the North China Plain (R4), middle and lower Yangtze River region (R7), and southern China (R8).
4) Short duration ("monthly," "intra-seasonal," "cross-seasonal") and low severity ("mild drought" and "moderate drought") are the dominant factors for the joint return periods of various drought events in China.

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