

Postprint of SPEI-based Multi-scale Analysis of Dry-wet Characteristics in the Yellow River Basin

Authors: Gao Bingli

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Abstract

Based on daily observation data from 70 meteorological stations in the Yellow River Basin from 1960 to 2020, the Standardized Precipitation Evapotranspiration Index (SPEI) was calculated using precipitation and potential evapotranspiration to investigate the evolution and persistence characteristics of dry-wet conditions in the Yellow River Basin from 1960 to 2020, and to analyze the influence of meteorological factors on dry-wet changes in the basin. The results show: (1) At different temporal scales, the dry-wet grades and frequencies reflected by SPEI exhibit certain differences, with normal and mild grades being predominant; in terms of interannual variation, the summer season in the Yellow River Basin from 1960 to 2020 shows an insignificant wetting trend, while the annual, spring, autumn, and winter seasons all show insignificant drying trends. At the spatial scale, summer is dominated by wetting, with the proportion of stations showing an upward trend in SPEI accounting for 64.29% of the total stations; the basin's annual, spring, autumn, and winter seasons are dominated by drying, with the proportions of stations showing a downward trend in SPEI being 51.43%, 62.86%, 64.29%, and 51.43%, respectively. (2) From the perspective of different temporal scales of dry-wet events, 1970-1979 represents a typical dry period, while 1960-1969 represents a typical wet period, with the occurrence frequency of dry-wet events being: autumn > summer > spring > winter. (3) From the perspective of persistence characteristics of dry-wet events, the intensity of persistent drought events has increased, occurring mainly in autumn and winter; the intensity of persistent wet events has increased, occurring mainly in autumn. (4) The annual SPEI in the Yellow River Basin from 1960 to 2020 shows a downward trend, which is mainly driven by the combined effects of decreasing precipitation, mean wind speed, and relative humidity.

Full Text

Analysis of Multi-Scale Dry-Wet Characteristics in the Yellow River Basin Based on SPEI

GAO Bingli, GONG Jie, LI Yan, JIN Tiantian

College of Earth and Environmental Sciences/Key Laboratory of Western China's Environmental Systems, Ministry of Education, Lanzhou University, Lanzhou 730000, Gansu, China

Abstract

Based on daily observational data from 70 meteorological stations in the Yellow River Basin from 1960 to 2020, the Standardized Precipitation Evapotranspiration Index (SPEI) was calculated using precipitation and potential evapotranspiration. This study investigated the evolution and persistence characteristics of dry-wet conditions in the Yellow River Basin and analyzed the influence of meteorological factors on basin-wide dry-wet changes. The results indicate that: (1) There were certain differences in the dry-wet grades and frequencies reflected by SPEI at different time scales, with normal and light grades being dominant. In terms of interannual variation, the Yellow River Basin showed an insignificant wetting trend in summer, while annual, spring, autumn, and winter showed insignificant drying trends from 1960 to 2020. Spatially, summer was dominated by wetting trends, with 64.29% of stations showing increasing SPEI, whereas annual, spring, autumn, and winter were dominated by drying trends, with 51.43%, 62.86%, 64.29%, and 51.43% of stations showing decreasing SPEI, respectively. (2) From the perspective of different time scales of dry-wet events, 1970-1979 was a typical dry period, while 1960-1969 was a typical wet period. The frequency of dry-wet events followed the pattern: autumn > summer > spring > winter. (3) Regarding persistence characteristics, the intensity of persistent drought events increased, occurring mainly in autumn and winter, while the intensity of persistent wet events also increased, occurring mainly in autumn. (4) The weak decreasing trend of SPEI from 1960 to 2020 was primarily caused by the combined effects of decreasing precipitation, average wind speed, and relative humidity.

Keywords: Standardized Precipitation Evapotranspiration Index; dry-wet change; persistence; Yellow River Basin

Introduction

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report indicates that global warming is an undeniable fact [1]. Climate warming accelerates global and regional water cycles, altering water balance processes such as precipitation, runoff, and evapotranspiration, which significantly impacts regional climatic dry-wet conditions and water resource supply-demand balance, thereby affecting agricultural production, economic development, and

ecological environmental quality [2-4]. Consequently, studying dry-wet changes holds practical significance for preventing and controlling regional climate events such as droughts and floods and for socioeconomic development [5]. Currently, the Standardized Precipitation Evapotranspiration Index (SPEI) is widely used to characterize regional dry-wet changes, as it comprehensively considers the effects of evapotranspiration and precipitation, combining the sensitivity of the Palmer Drought Severity Index (PDSI) with the multi-scale, multi-spatial characteristics of the Standardized Precipitation Index (SPI) [6]. Numerous scholars have employed SPEI to investigate spatiotemporal evolution characteristics of dry-wet climate conditions.

The Yellow River Basin, located in the mid-latitudes of the Eurasian continent, mostly belongs to China's arid and semi-arid regions, representing a climate-sensitive zone and ecologically fragile area. Influenced by its geographical location and East Asian monsoon climate, the basin has inherently insufficient water resources and uneven precipitation distribution, making it one of China's most drought-prone areas, with a saying "nine droughts in ten years" [7]. Particularly in recent decades, under the combined effects of climate change and human activities, temperatures in the Yellow River Basin have risen significantly, drought frequency has increased markedly, and impacts have intensified, posing great risks to grain production, energy supply, urban water supply, and ecological environment [8]. The increasingly prominent drought problem has become a major obstacle to economic development in the Yellow River Basin. Previous studies have investigated dry-wet changes across China and in specific regions [9-12], with some focusing on the Yellow River Basin. These studies found that drought severity in the Yellow River Basin has intensified [13-15], and research based on other drought indices reached similar conclusions, demonstrating that SPEI-based studies effectively reveal dry-wet characteristics in the Yellow River Basin. However, these studies calculated potential evapotranspiration using the Thornthwaite formula, which only requires temperature data and fails to comprehensively consider other natural factors affecting dry-wet changes, potentially overestimating drought trends and intensity under global warming [16]. Wang et al. [17] found that SPEI based on the Penman-Monteith formula is more suitable for assessing drought severity in the Yellow River source region because the Thornthwaite formula produces large calculation errors on the Tibetan Plateau. Research also indicates that SPEI based on the Penman-Monteith formula performs better in drought monitoring than that based on the Thornthwaite formula, particularly in arid regions [18]. Therefore, this study employs SPEI based on the Penman-Monteith formula to analyze dry-wet spatiotemporal evolution characteristics and persistence in the Yellow River Basin from 1960 to 2020, and explores the influence of different meteorological factors on basin dry-wet changes, providing reference for further understanding dry-wet events in the Yellow River Basin under global warming.

1.1 Study Area Overview

The Yellow River Basin is located in north-central China (95°53' ~119°05' E, 32°10' ~41°50' N), originating from the Bayan Har Mountains on the Tibetan Plateau and flowing through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong provinces before emptying into the Bohai Sea at Kenli County, Shandong, covering a total area of approximately 79.5×10^4 km². The basin has a multi-year average precipitation of 440 mm and multi-year average temperature of 9.2°C, with precipitation and temperature showing south-high-north-low and east-high-west-low patterns [19]. It should be emphasized that provinces mentioned in this paper refer only to the portions within the Yellow River Basin, not entire provincial regions [20]. The basin's terrain is highly undulating, spanning the Tibetan Plateau, Inner Mongolia Plateau, Loess Plateau, and Huang-Huai-Hai Plain from west to east. From west to east, the basin comprises arid, semi-arid, semi-humid, and humid zones, with the entire basin being a climate change-sensitive and ecologically fragile area.

1.2 Data Sources

Daily maximum temperature (Tmax), average temperature (Tavg), minimum temperature (Tmin), relative humidity (RH), sunshine duration (SD), and average wind speed (WS) data from 70 meteorological stations in the Yellow River Basin were obtained from the China Meteorological Data Network (<http://data.cma.cn/>). Stations with missing data not exceeding 5% were selected after data quality and validity checks, resulting in 70 stations with relatively complete data. Missing data and outliers were interpolated using the average value of that meteorological element for the same day [21].

1.3 Methods

1.3.1 Standardized Precipitation Evapotranspiration Index The SPEI was proposed by Vicente-Serrano et al. [22] based on SPI, characterizing regional dry-wet status through the degree of deviation of precipitation and potential evapotranspiration differences from average conditions. The key to SPEI calculation is potential evapotranspiration. Compared with the Thornthwaite formula, potential evapotranspiration obtained by the Penman-Monteith formula shows higher agreement with measured data in both arid and humid regions [23]. Therefore, this study calculates potential evapotranspiration based on the Penman-Monteith formula, using the research results of Liu et al. [24] to modify net radiation in the Penman-Monteith formula to better suit the Yellow River Basin. The specific calculation process is detailed in reference [22]. SPEI has multi-time scale characteristics: SPEI-1 (1-month scale) reflects monthly dry-wet conditions, SPEI-3 reflects seasonal dry-wet conditions, SPEI-6 reflects half-year dry-wet conditions, and SPEI-12 reflects annual dry-wet conditions [25]. This study selected SPEI-3 for March (spring), June (summer), September (autumn), and December (winter) to represent seasonal dry-wet conditions,

and SPEI-12 to represent annual dry-wet conditions. Dry-wet events were classified according to the standards in Table 1.

1.3.2 Climate Tendency Rate The climate tendency rate uses a unary linear regression equation to represent the change trend of a meteorological factor over a certain period. The formula is: $y = a + bt$, where y is the meteorological factor with sample size n ; t is the time corresponding to y ; a is the regression constant; b is the regression coefficient; a and b are calculated using the least squares method. In this paper, b is used as the climate tendency rate of meteorological factors, and the significance of the fitted regression equation is tested using F-test. The climate tendency rate is used to analyze SPEI and meteorological factor trends.

1.3.3 Partial Correlation Analysis Partial correlation analysis examines the correlation between two variables while controlling for other variables in a multi-variable system. When studying the correlation between two variables, other variables are treated as constants, and the result is a partial correlation coefficient. The formula is: $r_{.2} = (r_{xy} - r_{xz}r_{yz}) / \sqrt{(1 - r_{xz}^2)(1 - r_{yz}^2)}$, where $r_{.2}$ is the partial correlation coefficient between x and y controlling for z ; r_{xy} is the correlation coefficient between x and y ; r_{xz} is the correlation coefficient between x and z ; r_{yz} is the correlation coefficient between y and z . Partial correlation analysis is used to explore the influence of different meteorological factors on dry-wet changes in the Yellow River Basin.

2 Results and Analysis

2.1 Temporal Variation Characteristics of SPEI

2.1.1 Different Time Scales The sensitivity of SPEI to temporal variation differs across time scales: shorter time scales show more frequent dry-wet fluctuations, while longer time scales show smoother fluctuations. SPEI-1 showed the largest fluctuation amplitude from 1960 to 2020, indicating frequent dry-wet alternation under the influence of monthly precipitation and temperature. During the study period, normal, light drought (wet), moderate drought (wet), and extreme drought (wet) accounted for 55.87%, 16.53%, 14.62%, 6.01%, and 6.97% of all dry-wet events, respectively, showing that as dry-wet grades intensified, the proportion of corresponding events gradually decreased. Moderate drought occurred mainly in autumn, light drought occurred most frequently in spring, light wet occurred mainly in summer and winter, and moderate wet occurred most frequently in spring. Additionally, SPEI at different time scales in the Yellow River Basin showed decreasing trends, indicating gradual climate drying over the past 60 years.

SPEI-3 showed similar fluctuation characteristics to SPEI-1 but with smoother frequency. During the study period, normal, light drought (wet), moderate drought (wet), and extreme drought (wet) accounted for 55.75%, 16.16%,

16.99%, 5.48%, and 5.62% of all dry-wet events, respectively. Moderate drought and light wet occurred most frequently in autumn, light drought occurred most frequently in summer, and moderate wet occurred most frequently in spring.

SPEI-6 fluctuated frequently with an insignificant decreasing trend at a rate of $-0.003 \cdot a^{-1}$. Specifically, from 1960 to 2020, annual SPEI-6 showed 21 dry years and 20 wet years, with 2000 being a moderate drought year. Seasonally, summer SPEI-6 showed an increasing trend (wetting tendency) at a rate of $0.008 \cdot a^{-1}$, while spring, autumn, and winter SPEI-6 showed decreasing trends (drying tendencies) with negative tendency rates, though these trends were insignificant.

SPEI-12 showed that from 1960 to 2020, normal, light drought (wet), moderate drought (wet), and extreme drought (wet) accounted for 57.70%, 18.31%, 15.12%, 4.30%, and 4.57% of all dry-wet events, respectively. Moderate drought occurred slightly more frequently in spring and winter, light drought and light wet occurred most frequently in summer, and moderate wet occurred mainly in spring and winter.

2.2 Spatial Variation Characteristics of SPEI

Significant spatial differences in interannual variation of SPEI were observed in the Yellow River Basin from 1960 to 2020. For annual SPEI, stations with increasing and decreasing trends accounted for 48.57% and 51.43% of total stations, respectively. Stations with significant increasing trends were mainly distributed in northwestern Qinghai and northern Gansu, while stations with significant decreasing trends were mainly distributed in central Gansu and northwestern Ningxia. The spatial distribution of SPEI tendency rates is related not only to meteorological factors but also to atmospheric circulation and land-sea distribution.

For seasonal SPEI, spring showed decreasing trends at 64.29% of stations, mainly distributed in Gansu, most of Shanxi, and Shaanxi, with only 20.00% of stations passing significance tests, primarily located in northwestern Ningxia, and the northeastern and southwestern corners of Shaanxi. Summer SPEI showed increasing trends at 64.29% of stations, with 11.43% showing significant increases mainly in northwestern Qinghai and southwestern Shaanxi. Autumn SPEI showed decreasing trends at 62.86% of stations, mainly in Gansu, most of Shanxi, and Shaanxi, with only 18.57% passing significance tests, primarily in central Gansu. Winter SPEI showed decreasing trends at 51.43% of stations, mainly in central Gansu, with 35.71% showing significant decreases. In summary, except for summer, the number of stations with decreasing SPEI trends exceeded those with increasing trends for annual, spring, autumn, and winter scales, indicating drying trends in these periods.

2.3 Multi-Time Scale Characteristics of Dry-Wet Events

To understand the evolution characteristics of dry-wet events from 1960 to 2020, frequencies of dry-wet events in different decades and seasons were calculated

based on SPEI-1 and classification standards. The total frequency of dry-wet events in the Yellow River Basin showed an overall decreasing trend, with the smallest cumulative frequency (61.37%) in 2010-2020. Dry event frequency exceeded wet event frequency in all decades. Regarding dry event frequency, 1970-1979 showed the highest frequency, representing a typical dry period. For wet event frequency, except for 1960-1969 when light wet frequency exceeded moderate wet, moderate wet frequency was higher than light wet in other periods. Additionally, 1960-1969 had higher wet event frequency than other decades, representing a typical wet period.

Seasonally, dry-wet event frequencies were: autumn > summer > spring > winter. Extreme drought occurred most frequently in winter (1.76%), while extreme wet occurred most frequently in summer and autumn (1.67%). Light and moderate dry-wet events occurred at similar frequencies across seasons. Seasonal dry-wet conditions effectively reflect agricultural drought and flood conditions, suggesting that early warning systems should focus on winter drought and summer-autumn flooding for disaster prevention and mitigation.

2.4 Persistence Characteristics of Dry-Wet Conditions

Persistent dry-wet events cause more severe agricultural losses than single events. Using SPEI-1 data and classification standards, continuous processes with $\text{SPEI} \leq -0.5$ (light drought or above) for three or more months were defined as persistent drought events, and continuous processes with $\text{SPEI} \geq 0.5$ (light wet or above) for three or more months were defined as persistent wet events. The average SPEI value of the process was used as intensity, and duration reflected severity.

From 1960 to 2020, 21 persistent drought events occurred in the Yellow River Basin. Except for one event lasting 4 months, others lasted 3 months. These events occurred 8 times in the 1970s, 6 times in the 2000s, and 7 times in other decades. The strongest drought event occurred from September 1999 to January 2000 with an intensity of -1.76. The intensity of persistent drought events showed an increasing trend, occurring mainly in autumn and winter, with some spanning spring-summer and autumn-winter.

From 1960 to 2020, 20 persistent wet events occurred. Except for one event lasting 4 months, others lasted 3 months. These events occurred 6 times in the 1960s, 5 times in the 1970s and 1980s, and 4 times in the 1990s and 2000s. The strongest wet event occurred from September to November 1964 with an intensity of 1.67. The intensity of persistent wet events showed a slight increasing trend, occurring most frequently in autumn, followed by spring and winter, and least frequently in summer.

2.5 Analysis of Influencing Factors on Dry-Wet Changes

Dry-wet changes are influenced by precipitation and potential evapotranspiration, which is related to maximum temperature, average temperature, minimum

temperature, relative humidity, sunshine duration, and average wind speed. To explore influencing factors, partial correlation coefficients between annual SPEI and seven meteorological factors (precipitation, maximum temperature, average temperature, minimum temperature, relative humidity, sunshine duration, and average wind speed) were calculated for each station. The absolute values of partial correlation coefficients were: precipitation ($|r| = 0.52$) > relative humidity ($|r| = 0.28$) > sunshine duration ($|r| = 0.26$) > maximum temperature ($|r| = 0.24$) > average wind speed ($|r| = 0.22$) > average temperature ($|r| = 0.20$) > minimum temperature ($|r| = 0.18$). Precipitation and relative humidity were positively correlated with SPEI, while average wind speed was negatively correlated.

The spatial distribution of partial correlation coefficients between annual SPEI and meteorological factors showed that 91.43% of stations had positive precipitation correlations, with high absolute values in southwestern Gansu and central-southern Shaanxi. Relative humidity correlations were positive at all stations except Hezuo. Average wind speed correlations were negative at 98.57% of stations, with high absolute values in northwestern basin areas. The combination of meteorological factors with highest absolute partial correlation values showed that for 92.86% of stations, precipitation was the primary factor and average wind speed the secondary factor, distributed across most of the basin. Only two stations (Taishan and Hualing) had precipitation as primary and relative humidity as secondary factors. Two stations (Henan and Linfen) had precipitation as primary and sunshine duration as secondary factors. One station (Jingtai) had average wind speed as primary and precipitation as secondary factors.

Analysis of trends in precipitation, average wind speed, and relative humidity from 1960 to 2020 showed that precipitation decreased slightly, average wind speed decreased (relatively low in early and mid-1960s, high in mid-1970s, then decreasing), and relative humidity remained stable with a slight decreasing trend weaker than that of wind speed. The combined effects of decreasing precipitation, decreasing average wind speed, and decreasing relative humidity caused the weak decreasing trend in SPEI.

3 Discussion

This study used SPEI based on the Penman-Monteith formula to analyze spatiotemporal dry-wet change characteristics in the Yellow River Basin. The results show that except for summer, the basin experienced drying trends annually and in spring, autumn, and winter under climate change. Wang et al. [13] found that maximum and minimum temperatures were positive influencing factors, while average wind speed, sunshine duration, and average temperature were negative influencing factors. Previous studies indicated that precipitation and relative humidity were dominant factors for annual dry-wet changes in the Yellow River Basin [15], but this study found precipitation and average wind speed as dominant factors. This suggests precipitation is the primary controlling factor for dry-wet changes, but differences in secondary factors may result

from different dry-wet indicators and study periods.

This study has limitations. When exploring meteorological factors affecting dry-wet changes, only individual factor effects were considered, while correlations between different factors and comprehensive effects of multiple factors require further investigation. Dry-wet changes are also related to human activities, topography, and soil conditions. Integrating these factors with meteorological factors would provide clearer understanding of spatiotemporal variation patterns and abnormal distribution characteristics of dry-wet conditions.

4 Conclusions

- (1) SPEI at different time scales showed differences in dry-wet grades and frequencies, dominated by normal and light conditions. From 1960 to 2020, summer showed an insignificant wetting trend, while annual, spring, autumn, and winter showed insignificant drying trends. Spatially, summer was dominated by wetting trends, while annual, spring, autumn, and winter were dominated by drying trends.
- (2) From multi-time scale perspectives, 1970-1979 was a typical dry period and 1960-1969 a typical wet period. Dry event frequency exceeded wet event frequency. Seasonally, dry-wet event frequencies were: autumn > summer > spring > winter.
- (3) Regarding persistence, all persistent drought events lasted 3 months, occurring most frequently in autumn and winter. Persistent wet events occurred most frequently in autumn, followed by spring and winter, and least frequently in summer.
- (4) The weak decreasing trend of SPEI from 1960 to 2020 was mainly caused by combined decreases in precipitation, average wind speed, and relative humidity.

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