Postprint: Spatiotemporal Characteristics of Drought in Xinjiang Based on MSWEP Precipitation Products

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Abstract

Owing to the sparse and uneven distribution of precipitation stations in Xinjiang and the insufficient spatial representativeness of existing station-based drought monitoring data, the utilization of remote sensing precipitation products—which offer advantages such as extensive coverage, high spatial resolution, and favorable timeliness—holds significant importance for drought monitoring research in Xinjiang. The Multi-Source Weighted-Ensemble Precipitation (MSWEP) multi-source remote sensing precipitation fusion product has been widely applied across the globe. Under the background of climate warming, precipitation variability in Xinjiang has increased, and drought events have become more frequent. Based on data from 106 meteorological stations in Xinjiang, and following the error assessment of the MSWEP precipitation product, this study employs the MSWEP remote sensing precipitation product in conjunction with the Standardized Precipitation Index (SPI) to investigate dry-wet variations, drought events, and their fundamental characteristics in Xinjiang during the period 1980–2021. The results demonstrate: (1) MSWEP exhibits high correlation with station observation data (>0.8), and its accuracy essentially satisfies the requirements for drought monitoring; (2) Over the past 42 years, dry-wet changes in Xinjiang have been predominantly characterized by a wetting trend; (3) Since 1980, drought events have occurred frequently with diverse characteristics. Thirteen major drought events were identified, among which the drought event occurring during 1985–1987 represents the most severe drought event in the past 42 years, while the drought event from May to October 2009 constitutes the short-duration drought event with the highest intensity; (4) Drought events exhibit distinct characteristics in terms of duration, intensity, severity, etc., with some events featuring short duration but high intensity, while others display long duration but relatively low intensity. In conclusion, the MSWEP remote sensing precipitation product provides crucial data support for drought monitoring in data-scarce regions.

Full Text

Study on Spatiotemporal Characteristics of Drought in Xinjiang Based on Multi-Source Weighted-Ensemble Precipitation

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Abstract

Meteorological stations in Xinjiang are sparse and unevenly distributed, resulting in drought monitoring based on in-situ observations that is insufficient in spatial representativeness. Remote-sensing precipitation products offer advantages of wide coverage, high spatial resolution, and good timeliness, making them important for drought monitoring research in Xinjiang. The Multi-Source Weighted-Ensemble Precipitation (MSWEP) product has been widely applied worldwide. Against the background of climate warming, Xinjiang has experienced increased precipitation variability and frequent drought events. Based on 106 meteorological stations, this paper evaluates the accuracy of MSWEP remote-sensing precipitation products and combines them with the Standardized Precipitation Index (SPI) to analyze dry/wet variations, drought events, and their basic characteristics in Xinjiang from 1980 to 2021. The results show that: (1) MSWEP correlates well with station observations (correlation coefficient > 0.8), and its accuracy basically meets drought monitoring requirements; (2) Xinjiang's dry/wet changes are dominated by a wetting trend; (3) Since 1980, drought events have occurred frequently with diverse characteristics. Thirteen major drought events were identified, with the drought from 1985 to 1987 being the most severe, and the drought from May to October 2009 being the most intense short-term drought event; (4) Drought events exhibit varying characteristics in duration, intensity, and severity. Some events have short duration but high intensity, while others have long duration but low intensity. Overall, MSWEP remote-sensing precipitation products provide important data support for drought monitoring in data-scarce regions.

Keywords: MSWEP; drought monitoring; drought event; spatiotemporal characteristics; Xinjiang

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1 Study Area Overview

Xinjiang is located in the interior of the Eurasian continent, with geographic coordinates ranging from 73°40 -96°23 E and 34°25 -49°10 N. The region features diverse landforms, with the Altai Mountains in the north, Kunlun Mountains in the south, and the Tianshan Mountains traversing the central region. These mountain ranges divide Xinjiang into two major basins: the Junggar Basin in the north and the Tarim Basin in the south, forming a distinctive geographic pattern of "three mountain ranges alternating with two basins." This creates a unique landscape where mountain systems and basins alternate. The Tarim Basin is China's largest inland basin, with the Taklimakan Desert at its center being China's largest and the world's second-largest shifting desert. The Junggar Basin is China's second-largest basin, with the Gurbantunggut Desert at its center being China's second-largest desert.

Xinjiang's terrain generally slopes from high in the south and west to low in the north and east. The western ridge of the northern Altai Mountains has an average elevation above 3000 m, gradually decreasing eastward to low mountains and hills below 1000 m. The western Khan Tengri Peak in the Tianshan Mountains exceeds 5000 m, gradually decreasing eastward to low mountain landscapes at the border with Gansu. The Karakorum and Kunlun Mountains in the west average 6000 m in height, gradually decreasing eastward to 3000–4000 m. The Tarim Basin slopes from high in the west to low in the east, decreasing from 1400–1200 m to 780 m at Lop Nur. The Junggar Basin decreases from 3000 m in the northeast to 800–1000 m in the southwest, down to 179 m at Ebinur Lake.

Xinjiang has a typical continental arid climate with strong evaporation and scarce precipitation. Annual evaporation exceeds 1000 mm in plain areas, greater than 2500 mm in the Tarim Basin center, while the multi-year average precipitation is only 157.7 mm, less than one-quarter of the national average, making it China's most arid region. Drought occurs frequently, causing large-scale crop yield reductions or even total crop failure. According to Xinjiang Water Resources Department statistics, in 2008 alone, drought-affected crop area reached 8.13×10^{6} hm^2, with disaster-affected area of 4.27×10^{6} hm^2 and total drought losses of 2.31×10^{9} yuan. Xinjiang belongs to a typical continental arid climate zone and ecologically fragile region, making it particularly sensitive to global climate warming. Hu et al. [3] pointed out that Xinjiang's precipitation and temperature show an overall fluctuating upward trend. Shi et al. [4] indicated that Xinjiang is transitioning from warm-dry to warm-wet conditions. Xie et al. [5] analyzed that Xinjiang is undergoing a process of increasing temperature and humidity. Xuan et al. [6] analyzed drought characteristics in 14 regions of Xinjiang at seasonal and annual scales. Wang et al. [7] conducted drought prediction applicability studies in Xinjiang using CEEMD and ARIMA models. Yin et al. [8] analyzed spatiotemporal variation of drought in the Qaidam Basin using the SPEI index. Wang et al. [9] studied the applicability and differences of multiple drought indices in northern China. He et al. [10] compared drought monitoring indices based on multi-source data in southwestern China. Wang et al. [11] examined the applicability of four drought indices in Xinjiang. Lu et al. [12] studied multi-source precipitation products in Xinjiang. Hoyhazi et al. [13] analyzed spring and summer meteorological drought characteristics at county scale in Mulei County. Most previous research is based on observational station data, but limited station numbers in Xinjiang can cause bias. Therefore, this study uses the MSWEP remote-sensing station-merged product and selects the SPI to analyze spatiotemporal drought characteristics in Xinjiang, providing technical support for drought monitoring, early warning, and disaster reduction.

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2 Data and Methods

2.1 Data

2.1.1 Meteorological Station Data Monthly precipitation data from national meteorological stations were obtained from the National Meteorological Information Center (http://data.cma.cn/en) and China Meteorological Administration. The spatial distribution of stations is shown in [Figure 1: see original paper]. Monthly precipitation data from 106 stations during 1980–2021 were used to validate the accuracy of MSWEP precipitation products. All station precipitation data used in this study underwent strict quality control, including extreme value screening, internal consistency checks, spatial consistency screening, and missing value processing. As shown in the station distribution map, stations are unevenly distributed, relatively dense on the northern and southern slopes of the Tianshan Mountains, Altai Mountains, and Pamir Plateau, but sparse in the Tarim Basin desert area, Gurbantunggut Desert region, and almost absent in the southern Kunlun Mountains. Given Xinjiang's large spatial heterogeneity in station distribution and insufficient representativeness, station data were only used for precipitation product accuracy evaluation.

2.1.2 MSWEP Precipitation Product MSWEP integrates advantages of gauge precipitation data, satellite observations, and reanalysis data. It is one of the few remote-sensing precipitation products providing long time series precipitation data up to 40 years, with spatial resolution reaching 0.1°. It has been applied in many regions of China with good accuracy, meeting SPI calculation requirements and effectively compensating for poor spatial representativeness of Xinjiang' s observation stations [14]. MSWEP incorporates multiple remote-sensing precipitation datasets including GSMaP, CMORPH, and Gridsat B1, as well as infrared data from EUMETSAT, ECMWF reanalysis data (JRA-55), and WorldClim V2.0 climate dataset. Based on Global Historical Climatology Network (GHCN-D) and Global Summary of the Day (GSOD) observational data, MSWEP corrects merged precipitation errors to obtain final precipitation data [15]. This study used monthly MSWEP data from January 1980 to December 2021, obtained from http://www.gloh2o.org/mswep/.

2.2 Methods

2.2.1 Statistical Evaluation Metrics Based on Relative Bias (RB), correlation coefficient (R), and Fractional Root Mean Square Error (FRMSE), we established error evaluation metrics for precipitation products [16]. The formulas are:

$$RB = \frac{\sum_i (G_i - S_i)}{\sum_i G_i} \times 100$$

$$FRMSE = \frac{1}{N} \sum_i \frac{(S_i - G_i)}{G_i}$$

where S represents remote-sensing precipitation product, G represents gauge observation data, i represents sample sequence number, and N represents total sample size.

2.2.2 Sen' s Slope and Modified Mann-Kendall Trend Test Drought trend variation is an important indicator for drought monitoring. This study analyzed dry/wet change trends in Xinjiang and its subregions using Sen' s slope estimator and modified Mann-Kendall (MMK) significance test methods. Hamed and Rao [17] proposed the modified trend analysis method (MMK) that adds correction factors to the original variance calculation based on effective or equivalent sample size to avoid the impact of data autocorrelation. Numerous studies have proven that the MMK method is more reliable and stable in meteorological and hydrological research [18] and has been widely applied in drought trend analysis [19].

2.2.3 Standardized Precipitation Index The Standardized Precipitation Index (SPI), proposed by McKee et al. [20], is simple to calculate, requiring only precipitation data to quantitatively describe meteorological drought conditions in a region. It has flexible time scales and good spatial comparability [21] and has become one of the most widely used drought monitoring indicators [22]. Considering that collected gauge station data cannot meet the requirements for calculating evapotranspiration components in complex drought indices such as SPEI [23], this study selected SPI for drought monitoring research. SPI calculation mainly includes: (1) selecting an appropriate probability density function to describe the long-term rainfall time series; (2) calculating precipitation time series for corresponding time scales based on the required time scale; (3) fitting cumulative probability to the corresponding time scale in the precipitation time series; and (4) applying the inverse normal (Gaussian) function to the cumulative probability distribution function to generate SPI values.

The basic calculation formula is:

$$SPI = \frac{x - \bar{x}}{\sigma}$$

where x is precipitation amount; β and γ represent scale and shape parameters of the Gamma function respectively; S represents correlation coefficient; c_0, c_1, c_2, d_1, d_2, d_3 are calculation parameters with values $c_0 = 2.515517$, $c_1 = 1.432788$, $c_2 = 0.189269$, $d_1 = 0.802853$, $d_2 = 0.189269$, $d_3 = 0.001308$.

Studies have shown that 3-month SPI can well reflect local soil moisture deficits and has high correlation with surface natural vegetation and crop growth conditions [24]. Therefore, this study selected 3-month SPI as the drought research indicator. Its value range is [-3, 3], with positive values representing wet conditions and negative values representing drought. According to SPI values, dry/wet conditions can be classified as shown in .

2.2.4 Drought Event Identification and Quantitative Characterization Based on run theory [25], drought events were identified, and drought characteristics including start/end time, duration, intensity, severity, and peak were quantitatively analyzed. To ensure identification of different drought event types (e.g., low-intensity long-duration vs. short-duration high-intensity drought events), this study focused on drought events with relatively long duration and high drought peaks. Drought events were defined as periods with SPI < 0 lasting for 3 months or more. The times when SPI values start to become negative and recover to positive values are defined as drought start and end times. Drought duration is the number of months in drought status. Drought severity expresses the total severity of a drought event, defined as the cumulative SPI values (Equation 1). Drought intensity measures instantaneous severity, defined as the ratio of drought severity to drought duration (Equation 2). Drought peak is the minimum SPI value during the drought period, i.e., the SPI value of the driest month, with the corresponding month being the drought peak time (Equation 3). This study identified drought events pixel by pixel based on MSWEP precipitation data. To analyze spatial distribution of drought characteristics in Xinjiang, drought event characteristic indicators were averaged (Equations 4-7). Drought events and their basic characteristics are illustrated in [Figure 2: see original paper].

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3 Results

3.1 MSWEP Data Validation

This section validates MSWEP accuracy in Xinjiang and its subregions (northern, southern, and eastern Xinjiang) based on gauge data. (1) MSWEP monthly precipitation was extracted at station locations. (2) Spatial averages of gauge data and MSWEP were calculated for Xinjiang and three subregions to construct precipitation time series pairs. (3) Scatter plots were constructed based on spatially averaged time series, and correlation, relative error percentage, and fractional root mean square error were calculated.

[Figure 3: see original paper] shows that MSWEP has good overall accuracy in Xinjiang, with correlation coefficient reaching 0.84. Most scatter points lie above the 1:1 line, and the linear fitting line is approximately parallel to the 1:1 line, with relative error of 30.94% and FRMSE of 0.31, indicating that MSWEP has a certain degree of rainfall overestimation in Xinjiang, mainly systematic error. From a subregional perspective, linear fitting lines in scatter plots for southern and eastern Xinjiang also lie above and approximately parallel to the 1:1 line, indicating that rainfall overestimation mainly occurs in these regions. MSWEP shows overestimation of low-intensity precipitation but underestimation of high-intensity precipitation in northern Xinjiang, with overall precipitation underestimation (RB = -6.37%). Performance is poor in eastern Xinjiang, with correlation coefficient of 0.52 and rainfall overestimation reaching 37.06%, which is related to small precipitation base and sparse rain gauge distribution in this region. Overall, MSWEP performance in Xinjiang is satisfactory, with monthly precipitation correlation above 0.8, basically meeting remote-sensing drought monitoring application requirements, consistent with evaluation results from Guo et al. [14].

3.2 Drought Trend Analysis

Using 3-month SPI and the modified Mann-Kendall test method, the overall dry/wet change trend in Xinjiang from 1980 to 2021 was analyzed. [Figure 4: see original paper] shows that about 94.4% of Xinjiang exhibited a wetting trend during 1980–2021, with over 75.5% of regions showing significant wetting trends. Less than 6% of areas showed non-significant drying trends, mainly concentrated in the Tarim Desert region of southern Xinjiang. Regions with larger wetting amplitudes are mainly distributed in the Altai Mountains, Tianshan Mountains, and northern Karakorum Mountains. Over 75% of areas in northern and eastern Xinjiang show wetting signs.

At the regional scale, drought indices were calculated based on regionally averaged precipitation data to analyze temporal variations in Xinjiang and its three subregions. [Figure 5: see original paper] shows that Xinjiang' s overall wetting trend is significant, with a slope of 0.03/decade. During 1980–2021, the overall wetting trend is obvious. Northern, southern, and eastern Xinjiang all show overall wetting trends, consistent with spatial distribution. Since 2000, the wetting trend has slowed down.

3.3 Spatial Characteristics of Drought Events

To investigate drought events and their basic characteristics in Xinjiang, drought events were extracted pixel by pixel based on SPI and run theory. Drought event frequency and characteristics (severity, intensity, peak) were calculated pixel by pixel. [Figure 6: see original paper]a shows drought event frequency identified during 1980–2021, where higher frequency indicates more drought occurrences. High drought frequency occurs in the eastern Altai region of northern Xinjiang, the windward western slope of the Junggar Basin, the central southern Tianshan slope, and most areas of the Tarim Basin desert region. These areas experienced more than 10 drought events in the past 42 years. Lower drought frequency occurs in eastern Xinjiang, the northern Tianshan slope of northern Xinjiang, and northern Karakorum and Kunlun Mountains, with 5–8 drought events during 1980–2021.

[Figure 6: see original paper]b shows average drought duration of all drought events, i.e., average number of drought months. Longer average drought duration occurs in the southern Altai foothills, northern Tianshan slope, and east side of the Gurbantunggut Desert in northern Xinjiang, as well as in the Karakorum and northwestern Kunlun Mountains in southern Xinjiang, with average drought duration of 6–8 months.

Drought severity measures overall drought conditions and is influenced by both drought duration and intensity. [Figure 6: see original paper]c shows spatial distribution of average severity of all drought events. Regions with long drought duration generally have high severity, such as the southern Altai foothills in northern Xinjiang, Pamir Plateau, Karakorum Mountains, and western northern Kunlun Mountains, indicating that severity in these regions is mainly affected by long duration. Notably, western Tianshan and central northern Kunlun Mountains also show high drought severity, indicating that severity in these regions is mainly affected by high intensity ([Figure 6: see original paper]d).

3.4 Typical Drought Events Based on Regional Averages

Based on regionally averaged precipitation in Xinjiang, 3-month SPI was calculated and combined with run theory to identify drought events in the entire Xinjiang region and quantify their basic characteristics including duration, intensity, severity, and peak. Based on 3-month SPI, 13 drought events were identified. Basic characteristics of these events are shown in .

According to drought duration, severity, and intensity, four typical drought events were selected for detailed analysis. Typical Drought Event 1 (1985–1987) had the longest duration and highest severity. This drought lasted 21 months, peaking in June 1986 with SPI reaching -2.31, indicating extreme drought. Drought conditions returned to normal levels in September 1987. Total severity of this event reached -26.69. [Figure 7: see original paper]a shows spatial distribution of drought in Xinjiang during June 1986. The figure shows that 94.4% of Xinjiang was in drought status, with 75.5% in extreme drought, accounting for 75.5% of Xinjiang' s total area. Studies by Yao et al. [26] pointed out that extreme drought events occurred in Xinjiang during 1984–1987, mainly concentrated in western Xinjiang and Tianshan areas. Except for the Pamir Plateau region, all other regions were affected by this drought event. The central Tarim Desert region and northern Xinjiang were relatively lightly affected, mainly by mild and moderate drought.

Typical Drought Event 2 (1994–1996) belongs to the type with long duration but low intensity. Starting in May 1994 and ending in July 1996, this drought lasted 23 months but had low intensity of only -0.58, with severity of -13.42. In 1995, a typical drought year in Xinjiang, most regions were affected to some degree. 94.4% of Xinjiang was in drought status, but intensity was not high, mainly mild and moderate drought ([Figure 7: see original paper]b).

Typical Drought Event 3 (May–October 2009) was the most intense short-term drought event among all drought events, with intensity reaching -1.82, duration of 6 months, severity of -7.28, but intensity of -1.82. Such short-duration but high-intensity drought events can sometimes have greater impacts on ecosystems and vegetation than long-duration, low-intensity events. [Figure 7: see original paper]c shows spatial distribution of drought classes in the most severe month (July 2009). The figure shows that 94.4% of Xinjiang was in drought status, with about 75.5% in extreme drought, mainly distributed in western Tianshan, central regions, and middle section of the uninhabited Qiangtang area. Studies by Zhang et al. [27] on Xinjiang drought pointed out that the 2009 drought was a low-intensity, low-impact event mainly affecting southern Xinjiang. Xinjiang Water Resources Department [28] reported that in 2009, drought-affected crop area in Xinjiang reached 4.99×10^{5} hm^2, severely drought-affected grassland area was 1.83×10^{6} hm^2, and 3.78×10^{6} livestock suffered from drinking water shortages, with severe impacts in Kashgar, Kezhou, Aksu, Turpan, Hami, and Hotan regions.

Typical Drought Event 4 (July 2014–June 2015) had relatively high drought intensity of -1.15, with total severity of -10.38. [Figure 7: see original paper]d shows spatial distribution of drought classes in the most severe month (July 2014). The figure shows that the drought covered over 94.4% of Xinjiang, with severe and extreme drought area accounting for over 75.5%. Overall, southern Xinjiang was more severely affected, with most of the Tarim Desert region under severe and extreme drought classes. Northern Xinjiang drought was mainly concentrated in the southern Altai foothills, while eastern Xinjiang' s Turpan-Hami Basin mainly experienced moderate and mild drought.

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4 Discussion

Xinjiang' s meteorological stations are sparse and unevenly distributed, with almost no observation stations in the Tarim River desert area and Qiangtang uninhabited region. As a climate change-sensitive and ecologically fragile region, Xinjiang' s dry/wet changes and drought characteristics have attracted continuous attention. Drought monitoring relying solely on observation stations cannot effectively express spatial distribution of dry/wet changes and drought characteristics. Remote-sensing data have advantages of wide spatial coverage and good timeliness, effectively compensating for insufficient spatial representativeness of station data. With continuous accumulation of remote-sensing data, the time series length of some remote-sensing precipitation retrieval products has reached climate application research requirements. This study validated long-term multi-source merged MSWEP precipitation products using gauge observation data, fully utilized its characteristics of wide spatial coverage and low latency, identified drought events covering all of Xinjiang in recent years, and quantitatively analyzed their spatiotemporal characteristics.

The results show that MSWEP has high correlation with gauge data ($R > 0.8$), consistent with findings from Guo et al. [14]. The result that Xinjiang experienced slight wetting during 1980–2021 is consistent with Yao et al. [26]. It is worth noting that although MSWEP has high correlation with station data, it cannot directly replace gauge observations but can only provide spatially complete drought monitoring data. Xinjiang' s small number of stations and uneven distribution may affect MSWEP validation results. With continuous improvement of Xinjiang' s precipitation station network and continuous advancement of remote-sensing retrieval technology and gauge-remote-sensing fusion technology, drought monitoring accuracy in Xinjiang will continue to improve. The authors will continue to focus on research and application of ground station and remote-sensing product fusion.

5 Conclusions

This study aims to analyze drought development trends and spatiotemporal characteristics of drought events in Xinjiang from 1980 to 2021 using remote-sensing precipitation products. First, MSWEP remote-sensing precipitation products were validated based on meteorological station precipitation data. The results show that MSWEP meets drought monitoring requirements. Second, based on MSWEP-calculated SPI drought index, Xinjiang showed an overall wetting trend in recent years. This study defined drought events and quantitatively analyzed their characteristics. The results indicate that high drought frequency occurs in southern Tianshan, most of southern Xinjiang, and eastern Xinjiang; long average drought duration and high severity occur in southern Altai slopes, northern Tianshan slopes, and southwestern Xinjiang mountainous areas. Thirteen severe drought events were identified in Xinjiang. Among them, the drought from 1985 to 1987 was the most severe and longest lasting; the drought from May to October 2009 was the most intense short-term drought event in recent years. Drought events have different characteristics, with some having long duration but low intensity, and others having short duration but high intensity. These conclusions can provide scientific references for drought monitoring and disaster prevention and reduction in Xinjiang.

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