Spatiotemporal Characteristics and Influencing Factors of Heatwave- and Water-deficit-type Flash Droughts on the Loess Plateau: Postprint

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Abstract

Flash drought is a type of drought characterized by rapid development. In the context of global warming, flash droughts have occurred with increasing frequency and intensity in recent years, severely impacting agricultural ecosystems and human health in China. Understanding the spatiotemporal characteristics and influencing factors of flash drought events is crucial for their monitoring, early warning, and prevention. Based on ERA5-LAND data from 1981 to 2020, and using climate diagnostic methods such as trend analysis and correlation analysis, this study analyzes the spatiotemporal characteristics of heat wave-type and water shortage-type flash droughts in the Loess Plateau during the growing season (April–September). The results show that: (1) Over the past 40 years, the two types of flash droughts in the Loess Plateau have shown a fluctuating increasing trend. Specifically, the increasing rate of water shortage-type flash droughts [0.54 pentads · (10a)-1] exceeds that of heat wave-type flash droughts [0.46 pentads · (10a)-1]; In terms of interdecadal variation, the two types of flash droughts in the Loess Plateau exhibit similar patterns. Before 1998, the two types of flash droughts were dominated by low-level fluctuations; from 1998 to 2010, they increased rapidly; after 2010, the growth rate stagnated and exhibited a decreasing trend. (2) Spatially, 36.5% and 37.5% of the region exhibit a significant increasing trend ($P<0.05$) for heat wave-type and water shortage-type flash droughts, respectively. The loess hilly and gully region, eastern Hetao Plain, Fenwei River Valley Plain, and eastern Loess Plateau gully region represent common areas of significant increase for both types of flash droughts. (3) In terms of influencing factors, atmospheric pressure in northern Tibetan Plateau and sea surface temperature anomalies in the central equatorial Indian Ocean (0°-10°N, 50°-90°E) are significantly positively correlated with flash drought anomalies in the Loess Plateau growing season, that is, when atmospheric pressure in northern Tibetan Plateau and sea surface temperature

anomalies in the central equatorial Indian Ocean are anomalously high, the risk of both types of flash droughts in the Loess Plateau increases.

Full Text

Spatiotemporal Variation Characteristics and Influencing Factors of Heat Wave and Precipitation Deficit Flash Drought in the Loess Plateau

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Abstract: Flash drought is a type of drought characterized by rapid intensification. Against the backdrop of global warming, flash droughts have become increasingly frequent and severe in recent years, severely impacting China' s agricultural ecosystems and human health. Understanding the spatiotemporal characteristics and influencing factors of flash drought events is crucial for monitoring, early warning, and prevention. Based on ERA5-LAND data from 1981 to 2020 and using climate diagnostic methods such as trend analysis and correlation analysis, this study analyzes the spatiotemporal characteristics of heat wave and precipitation deficit flash droughts in the Loess Plateau during the growing season (April–September). The results show that both types of flash drought exhibited fluctuating increasing trends, with the precipitation deficit type increasing at a higher rate [0.54 penta $(10a)^{-1}$] than the heat wave type [0.46 penta $(10a)^{-1}$]. In terms of decadal variation, the two flash drought types showed similar patterns across the Loess Plateau. Before 1998, both types displayed low fluctuation. From 1998 to 2010, the number of flash droughts increased rapidly. After 2010, the growth rate stalled and began to decline. Spatially, significant increasing trends ($P < 0.05$) were observed in 36.5% of the region for heat wave flash drought and 37.5% for precipitation deficit flash drought. The gully-hill region of the Loess Plateau, eastern Hetao Plain, and Fenwei River Valley Plain showed marked increases in both types. Regarding influencing factors, the trend and interannual variability of flash droughts in the Loess Plateau correlate strongly with sea surface temperature anomalies in the NINO B region of the central equatorial Indian Ocean and atmospheric pressure anomalies over the northern Tibetan Plateau. Positive pressure anomalies over the northern Tibetan Plateau and large SST anomalies in the central equatorial Indian Ocean increase the probability of flash drought occurrence in the Loess Plateau.

Keywords: climate change; flash drought; spatiotemporal variation; ERA5-LAND; Loess Plateau

1 Study Area Overview

The Loess Plateau is located in north-central China, extending from the Qilian Mountains in the west to the Taihang Mountains in the east, from the Great Wall in the north to the Qinling Mountains in the south. It spans approximately 1,300 km east-west and 800 km north-south, with a total area of about 64.06$×10^{4}$ km^2, covering parts of Shanxi, Shaanxi, Gansu, Qinghai, Inner Mongolia, Ningxia, and Henan provinces. The region has a semi-arid continental monsoon climate, with precipitation concentrated in summer and decreasing from southeast to northwest, making it highly prone to drought events. Based on ecological zoning schemes and topographic characteristics, the study area is subdivided into seven sub-regions: Ningxia Plain, Hetao Plain, Mu Us Sandy Land, Loess Hilly-Gully Region, Loess Plateau Gully Region, Rocky Mountain Area, and Fenwei River Valley Plain [Figure 1: see original paper]. The Fenwei River Valley Plain, Hetao Plain, and Ningxia Plain are urban and agricultural centers, while the Loess Hilly-Gully Region and Mu Us Sandy Land are primary ecological restoration zones. The Loess Plateau Gully Region forms a transitional zone between semi-arid and arid climates and represents the upper reaches of the Yellow and Wei Rivers. The Rocky Mountain Area, primarily the Taihang Mountains, marks the eastern boundary of the Loess Plateau.

2 Data and Methods

2.1 Data Sources

The study uses hydrometeorological data including temperature, evapotranspiration, and soil moisture from the ERA5-LAND reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). This dataset represents an improved recalculation based on ERA5 land surface components, offering higher spatial resolution (0.1°) and temporal resolution (hourly). Soil volumetric water content is provided in four layers (0-7 cm, 7-28 cm, 28-100 cm, and 100-289 cm). The 100 cm depth layer was selected as it satisfies water and nutrient absorption requirements for most crop root systems. Atmosphere-ocean circulation indices were obtained from the Climate Change and Prediction Research Office of China' s National Climate Center.

2.2.1 Flash Drought Identification Process

Flash drought is identified when a region experiences both high temperature anomalies and abnormally low soil moisture. Soil moisture anomaly represents the direct factor affecting vegetation and crop growth. Two distinct mechanisms trigger flash drought: (1) short-term high temperatures (often accompanied by heat waves) that intensify soil evaporation and cause rapid soil moisture decline, defined as heat wave flash drought; and (2) precipitation deficits that reduce soil moisture and weaken evapotranspiration, leading through land-atmosphere coupling to abnormally high temperatures that further exacerbate soil moisture depletion, defined as precipitation deficit flash drought. The identification process

[Figure 2: see original paper] involves three criteria: (1) temperature condition—pentad temperature anomaly exceeding 1 standard deviation; (2) soil moisture condition—soil moisture below the 30th percentile; and (3) evapotranspiration condition—positive evapotranspiration anomaly for heat wave type versus negative anomaly for precipitation deficit type.

2.2.2 Trend Analysis

The Mann-Kendall trend test, a non-parametric statistical method robust to outliers and suitable for non-normally distributed data, was employed to analyze spatial variation characteristics of flash drought at each pixel. This approach comprehensively reflects flash drought evolution across the Loess Plateau over the study period. The standardized test statistic Z is calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases}$$

where $S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)$, x represents annual flash drought pentad counts, n is the study period length, and $Var(S)$ is the variance of statistic S. A positive Z indicates an upward trend, negative Z a downward trend, and $|Z| > 1.96$ (or > 2.58) indicates significance at the 95% (or 99%) confidence level.

2.2.3 Correlation Analysis

Regional-based spatial analysis was used to examine teleconnections between growing-season flash drought events across the Loess Plateau and its seven subregions with atmosphere-ocean indices. The Pearson correlation coefficient R_{xy} was calculated as:

$$R_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where x_i and y_i represent annual growing-season flash drought counts and atmosphere-ocean indices, respectively, and n is the study period length. This identifies key regions influencing Loess Plateau flash drought variability.

3 Results and Analysis

3.1.1 Temporal Variation of Two Flash Drought Types in the Loess Plateau

From 1981 to 2020, both flash drought types showed synchronized, fluctuating increasing trends [Figure 3: see original paper]. The precipitation deficit type increased at a higher rate [0.54 penta $(10a)^{-1}$] than the heat wave type [0.46 penta $(10a)^{-1}$]. Decadal analysis reveals three distinct phases: (1) 1981-1997—low fluctuation period with relatively stable heat wave flash drought and declining precipitation deficit flash drought; (2) 1998-2010—rapid increase period for both types, with precipitation deficit flash drought accelerating faster; and (3) 2011-2020—growth stagnation and decline period, though mean pentad counts remained above 1980s levels. The rapid increase phase corresponds to significantly more high-temperature days in the Loess Plateau since the mid-1990s, suggesting that regional warming provides an important climatic background for flash drought occurrence.

3.1.2 Temporal Variation in Seven Sub-regions

All seven sub-regions exhibit nonlinear, non-stationary, and stage-specific characteristics [Figure 4: see original paper]. The southeastern sub-regions (Loess Hilly-Gully Region, Loess Plateau Gully Region, Rocky Mountain Area, Fenwei River Valley Plain) showed turning points earlier than northwestern sub-regions (Ningxia Plain, Hetao Plain, Mu Us Sandy Land). For heat wave flash drought: (1) 1981-1997—low fluctuation in most sub-regions; (2) 1998-2010—rapid increase across all sub-regions; (3) 2011-2020—declining trends in Fenwei River Valley Plain, Loess Plateau Gully Region, and Ningxia Plain, while others stabilized. For precipitation deficit flash drought, patterns were more complex, with some sub-regions showing opposite trends during 1981-1997 but converging to consistent increases during 1998-2010.

3.3 Relationships Between Flash Drought and Atmosphere-Ocean Indices

Correlation analysis reveals that flash drought variability in the Loess Plateau is significantly associated with NINO B region SST anomalies, Atlantic Multidecadal Oscillation indices, and Tibetan Plateau pressure anomalies [FIGURE:5, FIGURE:6]. For heat wave flash drought, the Loess Plateau Gully Region and Fenwei River Valley Plain showed significant correlations with five atmosphere-ocean indices, while Hetao Plain and Rocky Mountain Area correlated with four, and Loess Hilly-Gully Region with three. For precipitation deficit flash drought, correlations were similar but slightly weaker with Atlantic indices. Notably, when SST anomalies are higher in the NINO B region (0°-10°N, 50°-90°E) and pressure anomalies are positive over the northern Tibetan Plateau (30°-40°N, 75°-105°E), flash drought risk increases substantially across the Loess Plateau. The mechanism involves asymmetric warming and snow cover anomalies over the Tibetan Plateau that weaken the East Asian summer monsoon, reducing precipitation over northern China.

4 Discussion

This study demonstrates that ERA5-LAND reanalysis data effectively identifies flash drought events in the Loess Plateau, consistent with previous research using GLDAS and other datasets. However, reliance on a single data source introduces uncertainty that should be addressed in future work through multi-source data integration. The identification of key teleconnection regions—particularly the NINO B region and northern Tibetan Plateau—provides new insights for flash drought monitoring and early warning. The physical mechanism linking Tibetan Plateau pressure anomalies to flash drought involves spring snow cover anomalies that alter surface albedo and heat fluxes, weakening the summer monsoon circulation and reducing precipitation over the Loess Plateau. This atmospheric dynamic process, combined with increasing temperatures, creates favorable conditions for rapid soil moisture depletion.

5 Conclusion

Based on ERA5-LAND reanalysis data from 1981-2020, this study analyzed spatiotemporal variations of heat wave and precipitation deficit flash droughts in the Loess Plateau and their responses to atmosphere-ocean indices. Key findings include: (1) Both flash drought types increased fluctuatingly, with precipitation deficit flash drought increasing faster than heat wave flash drought. Decadal variations showed three phases: low fluctuation (1981-1997), rapid increase (1998-2010), and stagnation/decline (2011-2020). (2) Spatially, heat wave flash droughts occurred more frequently in the eastern and southern mountainous areas ("less in northwest, more in southeast"), while precipitation deficit flash droughts showed the opposite pattern, concentrating in agricultural plains. Significant increasing trends covered 36.5% (heat wave) and 37.5% (precipitation deficit) of the region, with the gully-hill region, eastern Hetao Plain, Fenwei River Valley Plain, and eastern Loess Plateau Gully Region showing significant increases in both types. (3) Flash drought variability correlated strongly with NINO B region SST anomalies, Atlantic Multidecadal Oscillation, and Tibetan Plateau pressure anomalies. The Tibetan Plateau pressure index, through dynamic and thermodynamic effects on East Asian monsoon variability, showed the strongest relationship with flash drought anomalies in the Loess Plateau.

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