Spatiotemporal Characteristics and Trend Analysis of Precipitation in the Aral Sea Basin: Postprint

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Abstract

Based on the monthly precipitation series of the Aral Sea basin from 1945 to 2019 derived from the CRU (Climate Research Unit) dataset, this study analyzed the spatiotemporal characteristics of annual precipitation variation, intra-annual distribution of precipitation, and complexity changes in precipitation series using the climatic tendency rate, concentration degree and apportionment entropy, and sample entropy and permutation entropy methods, respectively. The Mann-Kendall method was employed to test the trends in the results obtained from each method. The results indicate that: the annual precipitation in the Aral Sea basin remained generally stable overall, showing a weak upward trend, with the northwestern and central-eastern regions of the basin exhibiting a significant upward trend; precipitation in the Aral Sea basin is concentrated around March each year, and the intra-annual distribution of precipitation shows a weak trend toward uniformization, with the western, northern, and eastern parts of the basin having a relatively more uniform intra-annual precipitation distribution, while the central and southern parts have a relatively more concentrated distribution; the complexity of precipitation series is relatively high in the western, northern, and eastern parts of the Aral Sea basin, and relatively low in the central and southern parts, with the overall complexity of precipitation series in the basin showing a certain upward trend, among which the complexity of precipitation series in the northern and southern parts shows a significant downward trend, while that in the western, central, and eastern parts shows a significant upward trend.

Full Text

Abstract

Based on monthly precipitation data from the Climate Research Unit (CRU) spanning 1945 to 2019, this study analyzes the spatiotemporal characteristics and trends of precipitation in the Aral Sea Basin. Using the climate tendency rate method, we quantified long-term changes in annual precipitation, while concentration period, concentration degree, and apportionment entropy were employed to characterize intra-annual distribution patterns. Sample entropy and permutation entropy methods were applied to assess the complexity of precipitation series. The Mann-Kendall test was used to evaluate the significance of trends in all derived indices. Results indicate that annual precipitation in the Aral Sea Basin remained largely stable with a slight increasing trend overall. Spatially, significant precipitation increases occurred in the northwestern and central-eastern regions. Precipitation was concentrated primarily in February each year, with a weak trend toward more uniform intra-annual distribution. The western, northern, and eastern parts of the basin exhibited relatively uniform precipitation distribution, whereas the central and southern regions showed more concentrated patterns. The complexity of precipitation series, as measured by sample entropy and permutation entropy, was relatively high in the western, northern, and eastern areas but lower in the central and southern regions. Basin-wide precipitation complexity showed an upward trend, with significant decreases in the north and south contrasting with significant increases in the west, center, and east.

Keywords: Aral Sea Basin; precipitation; inter-annual variability; intra-annual distribution; complexity

Introduction

Precipitation patterns and their temporal evolution serve as crucial indicators of climate change and have attracted considerable scholarly attention, particularly in arid and semi-arid regions where precipitation variability directly influences ecological processes and environmental succession. Central Asia represents one of the world' s largest arid zones, with the Aral Sea Basin serving as a typical watershed in the region. The "Aral Sea crisis" stems from severe imbalance between water resource replenishment and consumption, where unrestricted water withdrawal for economic development across basin countries, coupled with inefficient utilization and lack of effective regulatory mechanisms, has dramatically reduced inflow to the lake. Since 1960, the Aral Sea' s average water level has dropped from 53.78 m to 33.70 m, surface area has shrunk from 6.85×10^{4} km^2 to 0.83×10^{4} km^2 (an 87.88% reduction), and salinity has increased from 10 g$\cdot$L^{-1} to 70 g$\cdot$L^{-1}, causing severe ecological damage and an internationally recognized ecological disaster. While previous studies have examined climate change in Central Asia using moving averages, anomaly analysis, and correlation methods, most have focused on the lake itself or individual subbasins, with comprehensive research across the entire Aral Sea Basin remaining limited. This study analyzes precipitation amount, intra-annual distribution, and complexity across the full basin, providing scientific support for rational water resource development and ecological protection strategies in the region.

1.1 Study Area Overview

The Aral Sea Basin encompasses parts or all of seven countries: Kyrgyzstan, Kazakhstan, Tajikistan, Uzbekistan, Turkmenistan, Afghanistan, and Iran. The basin extends from the Tianshan Mountains and Pamir Plateau in the east to the western Turan Plain, from the Hindu Kush Mountains in the south to the Kazakh Hills in the north, covering a total area of 1.55×10^{6} km^2. Physiographically, the southern region features deserts, oases, and mountainous terrain, while the northern region consists of grasslands, plains, and hills, creating diverse landscape units.

1.2 Data Sources

Monthly precipitation data from 1945 to 2019 were obtained from the CRU TS v4.04 dataset (https://data.ceda.ac.uk/badc/cru/data/cru_{ts}/cru_{ts}4.04), which has a spatial resolution of $0.5° \times 0.5°$ and provides reliable representation of Central Asian climate variability. The dataset completely covers the entire basin boundary. For time series analysis using entropy methods, a sliding window approach was applied with window length t = 12 months and step size of 1 month, generating 900 time periods for analysis.

1.3 Research Methods

We employed multiple quantitative methods to characterize precipitation patterns. The climate tendency rate describes long-term linear trends in precipitation. Concentration period and concentration degree, based on vector analysis, quantify the timing and magnitude of precipitation concentration. Apportionment entropy evaluates the uniformity of intra-annual precipitation distribution. Sample entropy and permutation entropy measure the complexity and randomness of precipitation time series. All derived indices were subsequently tested for trend significance using the Mann-Kendall method.

1.3.1 Climate Tendency Rate The climate tendency rate represents long-term trend direction and magnitude through a linear equation. Larger values indicate more rapid and pronounced precipitation changes in a given region.

1.3.2 Concentration Period, Concentration Degree, and Apportionment Entropy Concentration degree and concentration period are vector-based parameters that characterize temporal distribution features of precipitation series. Higher concentration degree indicates more concentrated precipitation. Apportionment entropy serves as an important metric for evaluating uniformity—higher values indicate more uniform monthly distribution (maximum when monthly precipitation is equal), while lower values indicate concentration (minimum when all precipitation occurs in a single month).

1.3.3 Sample Entropy and Permutation Entropy Sample entropy measures time series complexity by quantifying the probability of generating new patterns, with larger values indicating greater complexity. For this analysis, we used embedding dimension m = 2 and threshold r = 0.2 times the standard deviation. Permutation entropy detects dynamical changes and randomness in time series, where larger values also indicate greater complexity. Parameters were set to embedding dimension m = 4 and delay time $\tau = 1$.

2.1 Annual Precipitation Change Characteristics

Annual precipitation in the Aral Sea Basin averaged 250.8 mm during 1945–2019, with a maximum of 390.0 mm and minimum of 175.6 mm. The Mann-Kendall test yielded Z = 1.21, which did not reach significance at the 0.05 level, indicating that annual precipitation remained essentially stable with a slight upward trend. Spatially, precipitation distribution showed substantial heterogeneity, with more precipitation in the eastern and southern regions and less in the western and northern areas. Specifically, southern Kazakhstan, central-western Uzbekistan, and southeastern Turkmenistan received relatively low amounts, while western Kyrgyzstan, central-western Tajikistan, and northeastern Afghanistan received relatively high amounts.

The spatial distribution of precipitation tendency rates revealed that significant increases occurred primarily in northwestern Uzbekistan, southwestern Kazakhstan, central-western Tajikistan, with smaller areas in northern Afghanistan and eastern Kyrgyzstan. These regions passed the 0.05 significance level test, confirming statistically significant upward trends in precipitation.

2.2 Intra-Annual Precipitation Distribution Characteristics

The concentration period of precipitation showed considerable spatial variation across the basin. Central and southern regions exhibited smaller values (concentrated in February-March), indicating winter-spring dominated precipitation, while northern and eastern regions showed larger values (concentrated in June-July), indicating summer-dominated precipitation. Temporally, the basin-wide concentration period showed a significant advancing trend ($Z = -3.02$, $p < 0.05$), meaning precipitation timing has shifted earlier.

Monthly precipitation distribution displayed a clear unimodal pattern, peaking in March at 42.8 mm (17.13% of annual total). The growing season (April-September) contributed only 34.54% of annual precipitation, while the non-growing season accounted for 65.46%. This asynchrony between water availability and crop water demand is characteristic of the region.

Both concentration degree and apportionment entropy series showed non-significant trends (Z = -0.42 and 1.38, respectively), indicating that intra-annual precipitation distribution remained largely stable with only a slight homogenization tendency. Spatially, concentration degree and apportionment entropy exhibited inverse patterns: Afghanistan' s western region, northern Tajikistan, and southeastern Turkmenistan showed higher concentration (lower uniformity), while northwestern Uzbekistan, southwestern Kazakhstan, and central Kyrgyzstan displayed lower concentration (higher uniformity).

2.3 Precipitation Sequence Complexity Characteristics

Spatial patterns of sample entropy and permutation entropy were similar, with lower values in the central and southern basin and higher values in the western, northern, and eastern regions. This indicates that precipitation series in the central and southern areas were more regular and predictable, while those in the west, north, and east exhibited greater complexity and uncertainty, making prediction more challenging.

Temporal analysis revealed that sample entropy (Z = 1.58) did not show a significant trend, while permutation entropy (Z = 2.04) showed a significant upward trend at the 0.05 level, suggesting increasing complexity over time. Both indices displayed distinct phases: sample entropy showed a decreasing-increasing-stable-decreasing pattern, while permutation entropy showed an increasing-stable-decreasing pattern. Notably, around 1990, precipitation series exhibited high randomness and complexity, while after the mid-2000s, uncertainty decreased and predictability improved.

The spatial distribution of change rates (Fig. 11) showed that sample entropy decreased in the northern and southeastern basin but increased in the western, central, and northeastern regions. Permutation entropy decreased in the southern and northern areas but increased in the western, central, and eastern regions. Combined analysis indicates that complexity and uncertainty decreased in central-eastern Tajikistan, northeastern Afghanistan, southwestern Kazakhstan, and northwestern Uzbekistan, while increasing in central Turkmenistan, southeastern Uzbekistan, and southeastern Kazakhstan.

Upstream countries (Kyrgyzstan, Tajikistan, Afghanistan) receive substantially more precipitation than downstream countries (Kazakhstan, Uzbekistan, Turkmenistan), with runoff contributions of 87.1% versus 12.9%, respectively. This spatial disparity in water resources, combined with concentrated agricultural water use in downstream plain irrigation areas, exacerbates water supply-demand conflicts and ecological vulnerability. The observed increase in precipitation may help alleviate these pressures, though the asynchrony between precipitation timing and crop growing seasons remains a critical challenge for water resource management.

3. Conclusions

Based on analysis of monthly precipitation series from 1945 to 2019, this study reveals the following key characteristics of precipitation in the Aral Sea Basin:

1) **Annual precipitation trends**: The basin averaged 250.8 mm annually, with a slight upward trend overall. Significant increases occurred in northwestern Uzbekistan, southwestern Kazakhstan, central-western Tajikistan, northern Afghanistan, and eastern Kyrgyzstan. Precipitation was more abundant in the southeastern plateau and mountain regions compared to the northwestern plain and arid areas.

2) **Intra-annual distribution**: Precipitation concentrated primarily around February, with a significant trend toward earlier timing. While the overall distribution remained stable, a weak homogenization tendency was observed. The western, northern, and eastern regions showed relatively uniform distribution, whereas the central and southern regions exhibited more concentrated patterns.

3) **Precipitation complexity**: Sample entropy and permutation entropy revealed higher complexity in the eastern, western, and northern basin compared to the central and southern regions. Basin-wide complexity showed an upward trend, with significant decreases in central-eastern Tajikistan, northeastern Afghanistan, southwestern Kazakhstan, and northwestern Uzbekistan, but significant increases in central Turkmenistan, southeastern Uzbekistan, and southeastern Kazakhstan.

These findings provide a scientific basis for national water resource policies and enhanced transboundary cooperation in the Aral Sea Basin, highlighting the need for region-specific strategies that account for the diverse spatiotemporal characteristics of precipitation.

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