Spatiotemporal Variation Patterns and Driving Factors of Evapotranspiration in the Aksu River Basin: A Postprint

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Abstract

Evapotranspiration, as a critical component of the water cycle, is essential for water resource regulation and ecological protection, playing a particularly important role in water consumption and redistribution in arid regions. This study takes the Aksu River Basin as the research area, utilizing MOD16 evapotranspiration product data from 2001 to 2022 to systematically analyze the spatiotemporal variation patterns of actual evapotranspiration (AET) and potential evapotranspiration (PET), and explores their influencing factors, providing a scientific basis for regional water resource management and ecological environmental protection. The results show that: (1) MOD16 product data is relatively consistent with ET0 data ($R^2 = 0.8133$); the product accuracy meets the requirements for studying the spatiotemporal distribution of evapotranspiration in the Aksu River Basin; (2) The multi-year average AET and PET are 168.36 mm and 1569.03 mm, respectively; AET shows an overall increasing trend, while PET shows a decreasing trend. AET and PET exhibit significant differences in spatial distribution and opposite changing trends; (3) Over the past 22 years, AET in the Aksu River Basin has increased significantly, mainly concentrated in cropland, forest land, and oases, while PET has decreased overall but increased near oasis edges and river channels. AET shows poor stability whereas PET is relatively stable. The Hurst exponent for both indicates that future trends may change, with 56% of the area showing anti-persistence for AET and 89% for PET; (4) Changes in AET and PET are intrinsically linked to variations in climatic factors, among which wind speed and relative humidity are the main driving factors influencing regional AET and PET changes. This study can provide important references for water resource management and scientific utilization in arid regions.

Full Text

Preamble

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Spatiotemporal Variation Patterns and Driving Factors of Evapotranspiration in the Aksu River Basin

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Abstract

Evapotranspiration, as a critical component of the water cycle, is essential for water resource regulation and ecological protection, particularly in arid regions where it plays a major role in water consumption and redistribution. This study examines the Aksu River Basin using MOD16 evapotranspiration product data to systematically analyze the spatiotemporal variation patterns of actual evapotranspiration (AET) and potential evapotranspiration (PET), and to explore their influencing factors, providing a scientific basis for regional water resource management and ecological conservation.

The results indicate that: (1) MOD16 product data show strong consistency with ET_0 data ($R^2 = 0.8133$, $p < 0.01$), demonstrating that the product accuracy meets the requirements for analyzing evapotranspiration distribution in the Aksu River Basin. (2) The multi-year average AET and PET are 168.36 mm and 1569.03 mm, respectively. AET exhibits an overall increasing trend, while PET shows a decreasing trend. The spatial distributions of AET and PET differ markedly, with opposite trends observed across the region. (3) Over the past 22 years, AET in the Aksu River Basin has increased significantly, primarily in cultivated land, forestland, and oases, whereas PET has decreased overall but increased near oasis edges and river channels. AET demonstrates poor stability while PET remains relatively stable. Both show potential future

trend reversals, with 56% of the region exhibiting anti-persistence for AET and 89% for PET. (4) Changes in AET and PET are intrinsically linked to climatic factors, with wind speed and relative humidity identified as the primary drivers influencing regional variations. This research provides an important reference for water resource management and scientific utilization in arid regions.

Keywords: evapotranspiration; water cycle; spatiotemporal variation; water resource management; Aksu River Basin

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1. Introduction

1.1 Study Area Overview

The Aksu River Basin is located on the southern slopes of the Tianshan Mountains and the northwestern edge of the Tarim Basin, forming the largest headwater region of the Tarim River. This study focuses primarily on the oasis portion of the basin (Figure 1), covering an area of approximately 1.5×10^4 km^2 within the geographic range of 78°89 –81°87 E and 40°17 –41°54 N. The region is characterized by a warm temperate extreme continental arid desert climate, with a multi-year average temperature of 10.7°C and annual precipitation of 50.4 mm. Soil types consist primarily of poplar forest soils (Tukay soils), and the dominant vegetation includes poplar, tamarisk, *Haloxylon*, and reed.

1.2 Data Sources and Processing

1.2.1 Remote Sensing Data The MOD16 global terrestrial evapotranspiration product includes actual evapotranspiration (AET), latent heat flux (LE), potential evapotranspiration (PET), and potential latent heat flux (PLE). The data are derived using the Penman-Monteith formula based on an algorithm developed in 2005. This study utilized monthly and annual AET and PET data from 2001 to 2022 (MOD16A2). The data were processed using the MODIS Reprojection Tool (MRT) for batch mosaicking, projection conversion, and transformation into WGS-1984 GeoTiff format.

1.2.2 Meteorological Data Meteorological data from the Aksu, Awati, and Alar stations for the period 2001–2022 were obtained from the National Meteorological Science Data Center and Urumqi Meteorological Bureau. Parameters included daily mean temperature, maximum temperature, minimum temperature, atmospheric pressure, wind speed, relative humidity, and sunshine duration. These data were used to calculate ET_0 values using the Penman-Monteith equation for validation of the remote sensing products.

1.3 Research Methods

1.3.1 Sen+MK Trend Analysis The Theil-Sen median slope estimation and Mann-Kendall trend test were employed to analyze trends in AET and

PET from 2001 to 2022. The Sen slope (β) is calculated as:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad \text{for } i < j$$

where x_j and x_i represent the AET/PET time series values. A positive β indicates an increasing trend, while a negative β indicates a decreasing trend.

The Mann-Kendall test statistic S is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)$$

where sgn is the sign function. For large samples (n > 10), S approximates a normal distribution with mean zero and variance:

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18}$$

The standardized test statistic Z is then calculated as:

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

A two-tailed test at significance level $\alpha = 0.05$ was used to determine trend significance (|Z| > 1.96). Trend classification criteria are presented in Table 1.

1.3.2 Coefficient of Variation The coefficient of variation (C) was used to assess the stability of AET and PET spatial patterns:

$$C_v = \frac{\sigma}{\bar{x}}$$

where σ is the standard deviation and $\bar{x}$ is the multi-year mean. Variability was classified as: very stable (C < 0.1), stable (0.1 ≤ C < 0.2), unstable (0.2 ≤ C < 0.3), and very unstable (C ≥ 0.3).

1.3.3 Hurst Analysis Hurst analysis was applied to evaluate the persistence of AET and PET trends. For time series ET (i = 1, 2, …, n), the mean series is:

$$\overline{ET}(t) = \frac{1}{t} \sum_{i=1}^{t} ET_i \quad t = 1, 2, \ldots, n$$

The cumulative deviation is:

$$R(t) = \max_{1 \le i \le t} \left(\sum_{i=1}^{t} (ET_i - \overline{ET}(t)) \right) - \min_{1 \le i \le t} \left(\sum_{i=1}^{t} (ET_i - \overline{ET}(t)) \right)$$

The standard deviation is:

$$S(t) = \sqrt{\frac{1}{t} \sum_{i=1}^{t} (ET_i - \overline{ET}(t))^2}$$

The Hurst exponent (H) is derived from the relationship $R(t)/S(t) = ct^H$. When H > 0.5, the series exhibits persistence; when H $= 0.5$, it shows randomness; and when H < 0.5, it demonstrates anti-persistence. Future trend classification criteria are shown in Table 2.

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2. Results

2.1 MOD16 Data Validation

To assess the applicability of MOD16 data in the Aksu River Basin, ET_0 values were calculated using the Penman-Monteith equation for the Aksu, Awati, and Alar meteorological stations and compared with MOD16-PET data. Since both ET_0 and PET estimate potential evapotranspiration under given meteorological conditions without water limitation, they are directly comparable. The correlation analysis revealed a strong relationship ($R^2 = 0.8133$, $p < 0.01$) between Penman-Monteith simulated ET_0 and MOD16-PET (Figure 2), confirming that MOD16 data are suitable for analyzing spatiotemporal evapotranspiration patterns in the study area.

2.2 Spatiotemporal Characteristics of AET and PET

2.2.1 Interannual Variation Annual AET fluctuated between 102.44 mm and 228.09 mm, with a multi-year average of 168.36 mm. The most pronounced fluctuations occurred in 2004 (-22.94%) and 2010 (37.99%), reflecting significant variations in water availability. PET ranged from 1480.65 mm to 1659.83 mm, averaging 1569.03 mm, with the largest variations in 2004 (7.55%) and 2010 (-10.79%). The substantial difference between AET and PET indicates that the region experiences severe arid conditions and water scarcity (Figure 3).

2.2.2 Spatial Distribution The spatial distribution of multi-year average AET and PET shows contrasting patterns (Figure 4). AET decreases from north to south, ranging from 0 to 344.3 mm, while PET increases from north to south, ranging from 1074.79 to 1919.17 mm. High AET values correspond to areas with dense vegetation cover, whereas high PET values occur in sparsely vegetated regions. Blank areas in the MOD16 product represent deserts, water bodies, unused land, and built-up areas where the algorithm cannot retrieve valid data due to limitations in using leaf area index to represent soil moisture conditions.

2.3 Dynamic Change Characteristics

2.3.1 Interannual Trends Sen+MK trend analysis reveals that AET increased significantly across 94.96% of the basin, primarily in cultivated land, forestland, and oases, while only 3.57% of built-up areas showed significant decreases. Conversely, PET decreased across 83.25% of the region but increased significantly near oasis edges and river channels (9.39%). The area of AET increase far exceeds that of decrease, while PET shows the opposite pattern (Figure 5; Table 3).

2.3.2 Interannual Variability The coefficient of variation analysis indicates that AET is highly unstable, with unstable and very unstable areas comprising 38.86% of the basin, while very stable areas account for only 0.16%. In contrast, PET exhibits remarkable stability, with very stable areas covering 92.85% of the region and stable areas covering 3.56%, totaling nearly 96.41% of the study area. Unstable areas represent only 0.03% of PET distribution, with no very unstable areas observed (Figure 6; Table 4).

2.3.3 Persistence Characteristics Hurst analysis shows that AET has a mean H value of 0.44, with 56% of pixels exhibiting anti-persistence ($H < 0.5$), suggesting future trend reversals. These anti-persistent areas are concentrated in regions with currently significant AET increases, indicating that growth trends may cease or reverse. PET has a mean H value of 0.41, with 89% of the region showing anti-persistence, while only 11% demonstrates persistence (Figure 7).

2.4 Influencing Factors

Correlation analysis between meteorological factors and AET/PET reveals distinct relationships (Table 5). AET is positively correlated with temperature, wind speed, vapor pressure, and sunshine duration, but negatively correlated with relative humidity. Specifically, AET shows a significant positive correlation with wind speed ($r = 0.817$, $p < 0.01$) and a significant negative correlation with relative humidity ($r = -0.606$, $p < 0.01$). PET, however, is positively correlated with temperature, relative humidity, and sunshine duration, but negatively correlated with wind speed and vapor pressure. Notably, PET exhibits a significant negative correlation with wind speed ($r = -0.446$, $p < 0.05$). These results demonstrate that wind speed and relative humidity are the primary drivers of AET and PET variations in the Aksu River Basin.

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3. Discussion

As the core hydrological unit of the Tarim River system, the Aksu River Basin provides the most significant perennial water supply to the mainstream and serves as a critical ecological barrier against desertification. Despite previous research on PET using various methods, systematic studies on long-term spatiotemporal dynamics and sustainability predictions remain limited. This study addresses this gap using MOD16 data and meteorological observations.

The increasing AET trend reflects multiple factors, including enhanced snowmelt from global warming and improved water use efficiency through advanced irrigation techniques (e.g., drip irrigation), which reduce water stress during growing seasons. The decreasing PET trend reveals an "evaporation paradox" consistent with findings in other arid regions. Spatially, the contrasting north-south patterns of AET and PET can be explained by the complementary relationship theory: in water-sufficient areas (farmland, oases), AET approaches PET, while in water-limited areas (deserts, gobi), reduced AET leads to increased PET due to enhanced land-atmosphere interactions.

Trend analysis shows significant AET increases in vegetated areas, likely due to improved vegetation cover and ecosystem function, while PET decreases overall but increases near oasis edges, possibly influenced by radiation forcing and humidity changes. The high variability of AET compared to PET's stability reflects the impacts of water resource management policies, irrigation improvements, and land cover changes on actual water consumption, whereas PET remains more constrained by stable climatic conditions.

Hurst analysis reveals anti-persistence for both AET and PET, suggesting that current trends may reverse due to complex interactions among land use changes, water management policies, and climate factors. This instability poses challenges for agricultural production and water resource management. The identification of wind speed and relative humidity as primary drivers enhances understanding of evapotranspiration mechanisms and provides a scientific basis for future water management under climate change.

Future research should focus on the long-term impacts of climate change and human activities, particularly extreme events and land use changes, to provide more precise guidance for ecological protection and water resource management in the Aksu River Basin.

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4. Conclusions

This study validated MOD16 evapotranspiration products using the Penman-Monteith equation and analyzed the spatiotemporal variations and trends of AET and PET in the Aksu River Basin from 2001 to 2022, along with their meteorological drivers. The main conclusions are:

1. **Data Validation**: MOD16-PET data correlate highly with Penman-Monteith simulated ET_0 values ($R^2 = 0.8133$, $p < 0.01$), confirming that MOD16 data are suitable for analyzing evapotranspiration patterns in the Aksu River Basin.
2. **Interannual Variation**: From 2001 to 2022, AET ranged from 102.44 to 228.09 mm (mean: 168.36 mm) and showed an increasing trend, while PET ranged from 1480.65 to 1659.83 mm (mean: 1569.03 mm) and exhibited a decreasing trend. Spatially, AET is higher in the north (vegetated areas) and lower in the south, whereas PET shows the opposite pattern, being higher in sparsely vegetated southern areas.
3. **Dynamic Change Characteristics**: Over the past 22 years, AET increased significantly across 94.96% of the basin, concentrated in cultivated land, forestland, and oases. PET decreased across 83.25% of the region but increased near oasis edges and river channels. AET is highly unstable (38.86% unstable or very unstable), while PET is predominantly stable (96.41% stable or very stable). The mean Hurst index for AET is 0.44, indicating anti-persistence in 56% of the region, while PET's mean H value of 0.41 shows anti-persistence in 89% of the area, suggesting potential future trend reversals.
4. **Influencing Factors**: Wind speed and relative humidity are the primary drivers of AET and PET variations. AET correlates significantly positively with wind speed ($r = 0.817$, $p < 0.01$) and negatively with relative humidity ($r = -0.606$, $p < 0.01$), while PET correlates significantly negatively with wind speed ($r = -0.446$, $p < 0.05$).

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