Postprint: A Study on Evapotranspiration Variation in the Yanqi Basin Based on MOD16 Data

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Abstract

Evapotranspiration is a critical variable in water resource transformation, particularly playing an important role in the spatiotemporal variation and prediction of crop water consumption in arid regions under current changing environments. Based on MOD16 data products from 2001 to 2019, and through remote sensing retrieval of evapotranspiration data, an analysis of the spatiotemporal variation of actual evapotranspiration (AET) and potential evapotranspiration (PET) in the Yanqi Basin was conducted. The results indicate: (1) The MOD16 evapotranspiration product shows good consistency with small evaporation pan measured data (R2=0.94), and its accuracy is sufficient for analyzing and investigating the spatiotemporal distribution characteristics of evapotranspiration in the Yanqi Basin. (2) The multi-year average AET and PET are 128.7 mm and 1381.5 mm, respectively; at the interannual scale, AET exhibits an upward trend while PET shows a downward trend. (3) The multi-year average AET and PET display distinct differential characteristics in spatial distribution and exhibit opposite trends; the linear slope rates of interannual AET and PET remain essentially unchanged. (4) The changing trends of AET and PET are intrinsically linked to the popularization of under-mulch drip irrigation technology in the Yanqi Basin and changes in meteorological elements (evaporation, relative humidity, average temperature).

Full Text

Study of the Variation Trend of Evapotranspiration in the Yanqi Basin Based on MOD16 Data

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Abstract

Evapotranspiration is a critical variable in water resource transformation, particularly for analyzing and predicting the spatiotemporal variation of crop water consumption in arid regions under changing environmental conditions. Based on MOD16 data products, this study analyzes the spatiotemporal variations of actual evapotranspiration (AET) and potential evapotranspiration (PET) in the Yanqi Basin through remote sensing inversion. The results demonstrate that: (1) MOD16 evapotranspiration products show strong consistency with small evaporation pan measurements ($R^2 = 0.94$), confirming their suitability for investigating the spatiotemporal distribution characteristics of evapotranspiration in the Yanqi Basin. (2) The multi-year average AET and PET are 128.7 mm and 1381.5 mm, respectively. At the interannual scale, AET exhibits an increasing trend while PET shows a decreasing trend. (3) The spatial distributions of multi-year average AET and PET display distinct differences and opposite patterns, with the linear trend rate remaining essentially stable. (4) These trends are intrinsically linked to the widespread adoption of mulched drip irrigation technology in the Yanqi Basin and changes in meteorological factors (evaporation, relative humidity, and mean temperature).

Keywords: MOD16 data; remote sensing evapotranspiration; water consumption trends; Yanqi Basin

Introduction

In the water cycle of arid and semi-arid regions, evapotranspiration represents the primary pathway of water consumption and, together with precipitation, determines the degree of aridity. It plays a crucial role in the rational allocation of water and land resources and in regional ecological balance research. Evapotranspiration research encompasses both actual evapotranspiration (AET) and potential evapotranspiration (PET). AET, the sum of soil evaporation and vegetation transpiration, is an essential component of hydrological cycles and surface energy balance, as well as a vital physiological process for vegetation survival. PET represents the maximum possible evapotranspiration from a fixed underlying surface under sufficient water supply conditions and serves as a key indicator for climate change and water resource studies in arid regions. As an important link connecting energy and water balance, accurate measurement and estimation of evapotranspiration are significant not only for scientific understanding of regional water cycle processes but also for climate evolution research, environmental issue analysis, and water resource evaluation.

With advancements in remote sensing technology, data from visible, near-infrared, and thermal infrared bands can reflect the spatiotemporal distribution of vegetation cover and surface temperature. Remote sensing-based evapotranspiration effectively captures regional water and energy balance, providing a new approach for regional evapotranspiration estimation. The MODIS sensor, as a new-generation resource satellite sensor, offers significant advantages for studying spatiotemporal distribution and variation trends of evapotranspiration in typical ecosystems. Domestic scholars have conducted spatiotemporal distribution studies of evapotranspiration in various regions using MOD16 data, including the Tarim River Basin, Qilian Mountains, Mu Us Sandy Land, and Sanjiang Plain. Additionally, Zheng Rongwei et al. explored the impact of different land use types and their conversions on water consumption in Beijing based on MOD16 data. Liu Ke et al. investigated the spatiotemporal distribution patterns and evolution of evapotranspiration in Ningxia grasslands from 2000 to 2014 using MOD16 products, discussing possible influencing factors. Tian Yichao et al. quantitatively analyzed the spatiotemporal variation characteristics of evapotranspiration in the Beibu Gulf coastal zone using MOD16 and vegetation type data, and predicted future trends.

Previous studies on evapotranspiration in the Yanqi Basin have primarily relied on meteorological observation data and field experiments. These studies were mostly conducted at the "point" scale, and scaling up the results to calculate evapotranspiration for the entire Yanqi Basin would introduce significant errors. In 2011, a U.S. research team made important achievements in evapotranspiration retrieval algorithms based on the Penman-Monteith formula and released global terrestrial evapotranspiration product data (MOD16) through MODIS. This data has been validated by global flux tower stations with simulation accuracy reaching 86%. MOD16 provides global land surface evapotranspiration data, with input data including leaf area index, albedo, vegetation coverage, and meteorological information such as air temperature, atmospheric pressure, relative humidity, and radiation. Output products include evapotranspiration, latent heat flux, potential evapotranspiration, and potential latent heat flux.

This study employs MOD16 data products to analyze the variation patterns of AET and PET in the Yanqi Basin from 2001 to 2019 through remote sensing inversion. The results reflect the evolution characteristics of irrigation methods and field water consumption in the basin in recent years, revealing new trends in water resource transformation. This research provides a new approach for calculating water consumption in oasis areas and offers technical support for water resource management under the strictest water resource management system, water transformation research, and the implementation of total water use control and ecological environment restoration measures in the Yanqi Basin.

1. Materials and Methods

1.1 Study Area The Yanqi Basin is a semi-enclosed intermountain basin located at the southern foothills of the eastern Tianshan Mountains in Xinjiang (Figure 1). Geographically situated between 82°50 -90°30 E and 39°06 -43°14 N, the basin covers an area of 1.3$\times 10^{4}$ km^2 and includes the administrative counties of Hejing, Heshuo, Yanqi, Bohu, and the 21st, 22nd, 25th, 26th, 27th, and 223rd regiments of the Xinjiang Production and Construction Corps. Located deep within the Eurasian continent, the basin experiences severe winters, rapid spring warming, mild summers, and rapid autumn cooling. As a climate transition zone between southern and northern Xinjiang, it exhibits typical arid region characteristics including abundant sunshine, substantial heat resources, large diurnal temperature variations, low precipitation, high evaporation, and dry air.

1.2 Data Sources

1.2.1 Remote Sensing Data MOD16A2 evapotranspiration data were obtained from the MODIS global terrestrial evapotranspiration product (downloaded from https://earthexplorer.usgs.gov/). The data have a spatial resolution of 500 m$\times$500 m and a temporal resolution of 8 days. Based on the product’ s orbital numbering pattern and the geographic location of the Yanqi Basin, data from satellite orbit numbers h24v04 and h25v04 were selected. The original data were converted to WGS-1984/Geographic coordinates using the MODIS Reprojection Tool (MRT), followed by resampling, projection transformation, and vector clipping using relevant tools in ArcGIS to remove invalid data.

1.2.2 Ground Observation Data To validate the accuracy of remote sensing data, monthly mean water surface evaporation data from small evaporation pans and meteorological data including average wind speed and temperature from 2001 to 2019 were collected from three meteorological stations (Yanqi, Hejing, and Bohu) within the basin.

1.2.3 Land Use Data Water consumption in the basin is directly related to different land use types. Land use data for the Yanqi Basin in 2018 with a spatial resolution of 30 m$\times$30 m were obtained from http://data.ess.tsinghua.edu.cn/. The original land use types were reclassified into six primary categories: cropland, forestland, grassland, water bodies, construction land, and unused land.

1.3 Methods

1.3.1 Linear Trend Analysis To quantitatively describe the variation trend of AET/PET and comprehensively reflect its spatiotemporal variation characteristics, linear trend analysis was employed to calculate the interannual variation trend and linear tendency rate (K) for each pixel. The calculation formula is:

$$K = \frac{n \times \sum_{i=1}^{n}(i \times ET_i) - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} ET_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where K is the linear tendency rate; n is the total length of the time series (n = 19); i is the specific year; and ET is the AET/PET value in year i. The magnitude of K indicates the tendency degree of AET/PET increase or decrease. A positive K value indicates an upward trend of AET/PET with increasing years, while a negative K value indicates a downward trend.

1.3.2 Coefficient of Variation The coefficient of variation (Cv) was used to analyze the stability of AET/PET spatial patterns in the study area. As an important indicator reflecting the variation degree of observations, Cv is the ratio of standard deviation to multi-year mean value. The calculation formula is:

$$Cv = \frac{\sigma}{\overline{ET}}$$

where σ is the standard deviation of each grid cell and $\overline{ET}$ is the multi-year mean value. To more intuitively reveal the spatiotemporal variation of evapotranspiration, Cv values were classified into three levels based on different ranges: slight fluctuation, moderate fluctuation, and significant fluctuation.

1.3.3 Relative Change Rate The relative change rate (r) was calculated to analyze interannual variation amplitude. The formula is:

$$r = \frac{ET_i - \overline{ET}}{\overline{ET}}$$

where r is the relative change rate, ET is the AET/PET value in year i, and $\overline{ET}$ is the multi-year mean value.

1.4 MOD16 Data Accuracy Validation To verify the accuracy of regional evapotranspiration data from remote sensing monitoring, three meteorological observation stations within the study area (Hejing, Yanqi, and Bohu) were selected for accuracy validation using measured monthly water surface evaporation from small evaporation pans (Figure 2).

AET represents the actual evapotranspiration process under real climate background and actual water and energy conditions, with its magnitude affected by both water availability and energy. In arid and semi-arid regions, abundant solar radiation is available. Meteorological station evaporation pan measurements represent maximum evaporation conditions of free water bodies under sufficient water supply, thus being influenced only by energy availability. PET represents the maximum possible evapotranspiration from a fixed underlying surface under sufficient water supply conditions. The correlation analysis between meteorological station measured evapotranspiration and PET (Figure 2) shows that evaporation pan measured water surface evaporation is highly correlated with PET, with a correlation coefficient of $R^2 = 0.94$. This indicates that MOD16 products meet accuracy requirements in the study area. Therefore, validating the applicability of MOD16 products in the Yanqi Basin through correlation between evaporation pan measurements and PET is feasible, and the data can be used to analyze and investigate the spatiotemporal distribution characteristics of evapotranspiration in the basin.

2. Results and Analysis

2.1 Interannual Variation Characteristics of Regional Mean AET and PET The interannual variation characteristics of AET and PET in the Yanqi Basin from 2001 to 2019 are shown in Figure 3. The multi-year average AET is 128.7 mm, fluctuating between 81.6–186.3 mm. The most prominent fluctuations occurred in 2004 and 2016, with relative change rates of -57.8% and 30.9%, respectively. The multi-year average PET is 1381.5 mm, fluctuating between 1294.8–1551.3 mm. The most prominent fluctuations occurred in 2005 and 2008, with relative change rates of 10.9% and -6.7%, respectively.

AET represents actual surface evapotranspiration, while PET represents maximum evapotranspiration under sufficient water supply conditions. The difference between the two can reflect the drought degree of the study area. Figure 3 shows that the annual difference is substantial, indicating overall drought and water shortage in the basin. The driest year was 2004, with a difference of 1432.8 mm. However, the difference shows a gradually decreasing trend from 2001 to 2019, indicating that soil moisture conditions in the basin have significantly improved, which should be directly related to changes in irrigation methods. Since 2002, mulched drip irrigation has been widely promoted locally, transforming irrigation from traditional furrow and border irrigation to well-based drip irrigation systems with headworks. This has significantly reduced water stress on crops during the growing season. Analysis of evaporation pan and relative humidity data from the Yanqi meteorological station partially confirms that increased relative humidity reduces PET, as PET is affected by relative humidity.

2.2 Spatial Distribution Characteristics of Multi-year Mean AET and PET The spatial distribution characteristics of multi-year mean AET and PET are shown in Figure 4. The ranges are 11.6–617.5 mm and 588.4–1769.1 mm, respectively, displaying obvious spatial distribution differences and opposite patterns. This opposite spatial distribution can be explained by the evapotranspiration complementary theory: when the underlying surface is sufficiently wet, AET equals PET; when water is insufficient, interaction between the surface and atmosphere leads to increased PET. The area around Bosten Lake shows AET values of 330.0–617.5 mm due to vegetation cover of reeds and oasis irrigation water diversion, which has significantly improved compared to previous conditions, with increasing water available for transpiration. The decreasing trend of PET from 2001 to 2019 is likely influenced by climate change, consistent with the "evaporation paradox" phenomenon observed in arid regions by some scholars in recent years.

In contrast, the piedmont plain areas and sandy lands and saline-alkali lands around the Gobi Desert show AET values of 11.6–117.4 mm and PET values of 1536.3–1769.1 mm due to high solar radiation, long sunshine hours, low precipitation, and insufficient water supply at the underlying surface. MOD16 products only cover vegetated areas, resulting in no data for Bosten Lake, unused land, and urban construction land.

2.3 Long-term Interannual Trend of AET and PET Using the linear trend calculation method and natural breaks classification, the spatial distribution of interannual linear trends of AET and PET in the Yanqi Basin from 2001 to 2019 is shown in Figure 5. Linear tendency rate K values were classified into five categories: severe decrease, slight decrease, basically unchanged, slight increase, and significant increase (Table 1).

AET shows a significant increasing trend west of Bosten Lake, in the Kongque River basin, and near the Wulasitai River, covering approximately 35.4% of the area. In terms of area proportion, the area with increasing trends exceeds that with decreasing trends. PET shows the opposite pattern, with decreasing trend areas significantly larger than increasing trend areas, accounting for 37.5% of the total area. The increasing trend of AET and decreasing trend of PET indicate that crop water demand in the irrigation area is gradually improving, mainly due to recent implementation of total water use control and over-exploitation management measures.

2.4 Interannual Fluctuation Degree of AET and PET After calculating fluctuation values, removing extreme values, and classifying using natural breaks, the interannual fluctuation degree of AET and PET in the Yanqi Basin is shown in Figure 6. The coefficient of variation (Cv) values were defined as three fluctuation intervals: slight fluctuation, moderate fluctuation, and significant fluctuation (Table 2).

AET shows predominantly slight fluctuation (55.7% of total area), mainly distributed in cropland; moderate fluctuation accounts for 33.8%, mostly in forestland and grassland; and significant fluctuation accounts for only 10.5%, distributed in low-lying areas around water bodies. PET shows slight fluctuation in 62.9% of the area, mainly in cropland of Hejing and Yanqi counties; moderate fluctuation in 35.3%, distributed in forestland and grassland of Hejing and Bohu counties and cropland and grassland of Heshuo County; and significant fluctuation in only 12.4%, located in marshlands around Bosten Lake. The mean linear tendency rates (K) for the entire basin are 0.02 for AET and -0.07 for PET, indicating basically unchanged interannual trends and relative stability. The largest fluctuations occur near water bodies, requiring future monitoring and management of natural vegetation in these areas to ensure effective implementation of total water use control.

3. Discussion

The evolution of water and land resources in the Yanqi Basin has been a research focus for many years. As an indispensable component of the water cycle, evapotranspiration plays a crucial role in the evolution of the water balance process in the Yanqi Basin. Based on MOD16 products and continuous meteorological observation data, this study analyzed the relationship between AET and PET and their long-term variation trends, revealing the evolution of water dissipation patterns in the basin. The determination of evapotranspiration provides a new data approach for water balance calculations in oasis areas.

With the expansion of drip irrigation areas, groundwater levels have continued to decline despite increased groundwater utilization, damaging the groundwater environment and leading to over-exploitation in some areas. The spatial distribution of AET and PET shows distinct differences and opposite trends. AET values of 330.0–617.5 mm in the Bosten Lake wetland area and oasis region indicate that continuous increases in evapotranspiration have exceeded the water resource carrying capacity of the irrigation area. In recent years, under requirements for total water use control, the Yanqi Basin has begun implementing farmland retirement and water reduction measures. To effectively assess regional water demand determination and annual water use assessment, continued annual monitoring of MOD16 data is recommended for future work. From the perspective of water consumption management, total water use in the region should be monitored to provide a basis for implementing water demand determination and ecological environment restoration measures.

4. Conclusions

1) Using measured evaporation data from three meteorological stations in the Yanqi Basin for reliability verification, the results show that measured water surface evaporation is highly correlated with MOD16 evapotranspiration products ($R^2 = 0.94$). The product accuracy meets requirements for analyzing and investigating the spatiotemporal distribution characteristics of evapotranspiration in the Yanqi Basin.

2) At the interannual scale, AET shows an increasing trend while PET shows a decreasing trend. The rise in AET will intensify water resource pressure in irrigation areas, while the decline in PET is related to climate change. These contrasting trends reflect that evapotranspiration patterns and climate in the Yanqi Basin may be undergoing evolution, which has important implications for water resource utilization and management in irrigation areas.

3) The spatial distributions of multi-year average AET and PET show distinct differences and opposite trends. The linear tendency rates are generally stable. The increasing trend of AET and decreasing trend of PET indicate that crop water demand in irrigation areas is gradually improving, primarily due to implementation of total water use control and over-

exploitation management measures.

4) In terms of interannual fluctuation, AET and PET have remained relatively stable overall. By land use type, cropland, forestland, and grassland are relatively stable, while the largest fluctuations occur near water bodies. Future research should focus on water consumption of natural vegetation and ecological protection zones, establishing a balanced relationship between irrigation and non-irrigation water consumption.

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