Characteristics and Attribution of Actual Evapotranspiration in the Arid Region of Central Asia Based on the Priestley-Taylor Method (Postprint)

Authors: Zhuoyi Zhao^{1,2,3}„ Hao Xingming[1,3]

Date: 2023-08-25T00:00:00+00:00

Abstract

Evapotranspiration constitutes the link between water-energy-carbon cycles. Understanding its dynamic processes and driving factors is of paramount importance for water resource stability, ecological security, and agricultural water management in the Central Asian arid region. This study, based on the Priestley-Taylor method, estimated and analyzed the spatiotemporal variations of evapotranspiration in the Central Asian arid region from 2000 to 2019. The Lindeman-Merenda-Gold method was employed to quantitatively evaluate the absolute contributions of different driving factors to each evapotranspiration component, and the contributions of each driving factor to evapotranspiration were assessed by weighting according to the contributions of each component to evapotranspiration changes. The results indicate that evapotranspiration in the Central Asian arid region exhibited a fluctuating increase at an overall rate of 1.45 $\mathrm{mm \cdot a^{-1}}$, with a spatial pattern of "increasing in the east and decreasing in the west". The trends of vegetation transpiration, evaporation, and canopy interception evaporation were 2.46 $\mathrm{mm \cdot a^{-1}}$, -1.03 $\mathrm{mm \cdot a^{-1}}$, and 0.02 $\mathrm{mm \cdot a^{-1}}$, respectively, contributing 70.09%, 29.34%, and 0.57% to evapotranspiration changes. NDVI was the dominant factor for vegetation transpiration and canopy interception evaporation, while air temperature was the dominant factor for evaporation. Overall, NDVI represents the dominant factor driving evapotranspiration changes in the Central Asian arid region, with an absolute contribution of 28.16%.

Full Text

Actual Evapotranspiration Characteristics and Attribution in Arid Central Asia Based on the Priestley-Taylor Method

ZHAO Zhuoyi[1],[2],[3], **HAO Xingming**[1],[3] [1]State Key Laboratory of Desert and Oasis Ecology, Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China [2]University of Chinese Academy of Sciences, Beijing 100049, China [3]Aksu National Station of Observation and Research for Oasis Agro-ecosystem, Aksu 843017, Xinjiang, China

Abstract: Evapotranspiration serves as the critical link between water, energy, and carbon cycles. Understanding its dynamic processes and driving factors is essential for water resource stability, ecological security, and agricultural water management in arid Central Asia. This study employed the Priestley-Taylor diurnal land surface temperature range (PT-DTsR) model to estimate and analyze spatiotemporal variations of evapotranspiration in the region. The Lindeman-Merenda-Gold method was used to quantitatively evaluate the absolute contributions of different drivers to each evapotranspiration component, and the contributions of each driver to total evapotranspiration were assessed by weighting according to each component' s contribution to overall evapotranspiration change. Results indicate that evapotranspiration in arid Central Asia increased at a rate of 1.45 $\mathrm{mm \cdot a^{-1}}$, exhibiting a distinctive spatial pattern of "increasing in the east, decreasing in the west." Vegetation transpiration, evaporation, and canopy interception evaporation changed at rates of 2.46 $\mathrm{mm \cdot a^{-1}}$, -1.03 $\mathrm{mm \cdot a^{-1}}$, and 0.02 $\mathrm{mm \cdot a^{-1}}$, respectively, contributing 70.09%, 29.34%, and 0.57% to the total evapotranspiration change. The Normalized Difference Vegetation Index (NDVI) emerged as the dominant factor driving evapotranspiration variability, with an absolute contribution of 28.16%.

Keywords: evapotranspiration; spatiotemporal variation; attribution; contribution; Central Asia; arid region

Introduction

The 2020 United Nations World Water Development Report, "Water and Climate Change," highlights that climate change challenges water resource stability, with water resources already under severe stress in many regions worldwide. Rapid socioeconomic development has further intensified global water supply-demand contradictions. Situated in the hinterland of the Eurasian continent, Central Asia is characterized by arid climate and scarce precipitation, where insufficient water resources have become a critical constraint on economic development and ecological security. As the primary water consumption term in the hydrological cycle, evapotranspiration exhibits an increasing trend globally, posing significant challenges to water resource security. Moreover, evapotranspiration functions as the crucial nexus connecting water, energy, and carbon cycles, serving as a key variable linking ecosystem functions, carbon-climate feedbacks, agricultural management, and water resources, and playing a pivotal role in terrestrial ecosystem carbon cycling and energy balance.

Evapotranspiration is a complex hydrological process influenced by numerous environmental factors. Dalton' s law establishes that evaporation correlates positively with saturation vapor pressure deficit and wind speed, while the Budyko framework conceptualizes evapotranspiration as a trade-off between surface water and heat conditions, with water and energy availability being the primary limiting factors. Variations in radiation, precipitation, temperature, specific humidity, and saturation vapor pressure deficit all affect evapotranspiration, with their relative contributions shifting according to regional water-heat conditions. Generally, evapotranspiration drivers can be categorized into three types: atmospheric evaporative demand (all meteorological factors except radiation), water supply (precipitation, etc.), and heat supply (radiation). Atmospheric evaporative demand represents the upper limit of evapotranspiration, water supply provides the material basis, and heat supply provides the energy driver.

Recent global vegetation greening has drawn considerable academic attention to vegetation impacts on evapotranspiration, with studies indicating that vegetation greening contributes up to 17-24% of global terrestrial evapotranspiration changes. Building upon these three driver categories, this study introduces vegetation activity as a fourth category representing surface biophysical processes.

Previous research has considered seasonal and regional differences in driving factors but overlooked variations among evapotranspiration components. Evapotranspiration comprises three distinct components: vegetation transpiration (ETc, hereafter transpiration), evaporation (ETs, including soil and water body evaporation), and canopy interception evaporation (ETi, hereafter interception). These components differ in water sources and underlying mechanisms. Analyzing only their sum obscures individual component characteristics and yields unrigorous interpretation of environmental factors' roles in water-heat processes. This study addresses these limitations by: (1) estimating spatiotemporal evapotranspiration patterns in Central Asia using the PT-DTsR model; (2) analyzing trends in each component and their contributions to total evapotranspiration change; and (3) quantifying driver contributions to each component and deriving weighted contributions to total evapotranspiration.

1.1 Study Area Overview

Arid Central Asia is located in the Eurasian continental interior between 34.33°-55.44°N and 46.50°-106.84°E, encompassing the five Central Asian countries (Kazakhstan, Tajikistan, Kyrgyzstan, Uzbekistan, Turkmenistan) and China' s northwestern arid region [Figure 1: see original paper]. The region features pronounced topographic relief and a mountain-oasis-desert landscape, with the Tianshan, Kunlun, Altai Mountains, Kazakh Uplands, Taklamakan Desert, Gurbantunggut Desert, Karakum Desert, and Turan Plain situated within its boundaries. Influenced by topography and continental location, oceanic moisture cannot reach the region, resulting in scarce precipitation with large spatial variability, making it one of the world' s most arid regions. In Central Asia, potential and actual evapotranspiration often exhibit opposite trends, approaching a complementary relationship.

1.2 Data Sources and Processing

Evapotranspiration data were estimated using the Priestley-Taylor diurnal land surface temperature range (PT-DTsR) model, with validation performed in our previous research. Meteorological data were obtained from the Global Land Data Assimilation System (GLDAS) version (https://disc.gsfc.nasa.gov/datasets?project=GLDAS), including specific humidity, wind speed, precipitation, air temperature, and radiation. Normalized Difference Vegetation Index (NDVI) data were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD13A2 product (https://appeears.earthdata.nasa.gov/).

1.3 Methods

1.3.1 Evapotranspiration Estimation

The PT-DTsR model, based on the Priestley-Taylor equation, calculates apparent thermal inertia from diurnal land surface temperature variation to replace relative humidity and vapor pressure deficit in quantifying soil moisture constraints. This simplification reduces data requirements and overcomes data scarcity issues in Central Asia. The model calculates potential values for each evapotranspiration component using the Priestley-Taylor equation, then applies environmental stress factors (soil moisture stress, temperature stress, etc.) to derive actual values. Detailed model description is available in the original literature.

1.3.2 Contribution Analysis

The Lindeman-Merenda-Gold method decomposes the coefficient of determination (R^2) into non-negative components, quantifying each explanatory variable' s contribution to the dependent variable. This metric uses the unweighted average of each variable' s sequential contributions across all available regressor permutations to avoid order effects. Component contributions to total evapotranspiration change were calculated by first determining each component' s contribution rate to interannual variability, then normalizing by absolute values.

1.3.3 Statistical Analysis

Pearson correlation coefficients combined with t-tests were used for correlation analysis and significance testing among different variables. The Theil-Sen median method combined with Mann-Kendall tests was employed for trend analysis and significance testing.

2.1 Spatiotemporal Variation Characteristics of Evapotranspiration

Mean annual evapotranspiration in arid Central Asia is approximately 149.62 mm, with lakes showing the highest values (>1000 mm) and the Kunlun Mountains the lowest (<50 mm). The annual trend exhibits a unique "west decreasing, east increasing" pattern, with increasing and decreasing trends covering 50.12% and 49.88% of the land area, respectively. The most significant increases occur in the Kazakh Uplands and oasis areas of northwestern China, while the most pronounced decreases appear in northwestern Kazakhstan [Figure 2: see original paper].

Seasonal evapotranspiration varies substantially, with summer values highest (39.34 mm), followed by spring (19.10 mm), autumn, and winter (3.90 mm). From spring to autumn, high evapotranspiration values primarily occur around lakes and the Altai and Tianshan Mountains (including northwestern Chinese oases), while Kunlun Mountains show the lowest values. Winter evapotranspiration decreases from south to north.

In seasonal trend analysis, summer shows the most pronounced changes, highly consistent with interannual variation. Spring increases concentrate around the Tianshan and Altai Mountains, while autumn and winter trends are insignificant.

2.2.1 Interannual and Intra-annual Variation Characteristics of Evapotranspiration Components

The interannual trend of evapotranspiration shifted around 2010, decreasing before 2010 and increasing thereafter, reaching maximum values in 2016 [Figure 3: see original paper]. Intra-annual variation follows a unimodal pattern, peaking in July. Evapotranspiration is dominated by evaporation and transpiration, with mean annual contributions of 63.15% and 36.30%, respectively, while interception accounts for only 0.55%. Evaporation is the largest component, with annual and monthly proportions exceeding 50% in most years. Transpiration proportion trends closely align with total evapotranspiration trends, rising and falling synchronously.

2.2.2 Spatial Distribution of Evapotranspiration Component Trends

Vegetation transpiration shows the most significant changes, contributing 70.09% to total evapotranspiration change despite comprising only 36.30% of the total. Transpiration increased at 2.46 $\text{mm} \cdot \text{a}^{-1}$, with increasing and decreasing areas covering 68.14% and 31.86% of the study region, respectively.

The most significant increases occur in oasis areas of northwestern China, while decreases are limited to Kazakhstan and northwestern Tianshan.

Evaporation decreased at -1.03 $\mathrm{mm \cdot a^{-1}}$, with negative and positive trends covering 63.33% and 36.67% of the area, respectively. The most pronounced decreases occur in water bodies (Balkhash Lake, Aral Sea, Issyk-Kul), exceeding -5 $\mathrm{mm \cdot a^{-1}}$, while increases appear in non-mountainous areas of northwestern China and around the Kopet Dag Mountains in the southern study area. In mountainous regions (Tianshan, Kunlun, Altai, Kazakh Uplands) and the Turan Plain, transpiration and evaporation show opposite trends, while in oasis areas they share similar trends but with transpiration changes exceeding soil evaporation changes.

Canopy interception evaporation trends are negligible and thus not mapped.

2.3.1 Correlation Analysis Between Evapotranspiration Components and Driving Factors

Vegetation transpiration correlates most strongly with NDVI ($r = 0.80$, $p < 0.001$) and significantly with precipitation, specific humidity, and downward shortwave radiation ($r = 0.45$, 0.42, 0.41, respectively, $p < 0.05$). While underlying vegetation conditions are the most direct driver, the other three factor categories also significantly influence transpiration.

Evaporation (including soil and water evaporation) shows the highest correlation with temperature ($r = -0.41$, $p < 0.001$), with opposite trends before 2010—temperature rising while evaporation decreased, suggesting a potential complementary relationship between potential and actual evapotranspiration. During this period, downward shortwave radiation decreased while precipitation continued declining. Rising temperatures coupled with decreasing precipitation intensified water supply-demand contradictions, likely causing persistent soil moisture decline that suppressed evaporation. Reduced latent heat from insufficient soil moisture may have increased sensible heat, raising temperatures and creating a positive feedback mechanism. After 2010, temperature and evaporation became positively correlated, with warming promoting evaporation. Evaporation also correlates strongly with specific humidity ($r = 0.37$, $p < 0.001$), with significant differences before and after 2010, indicating that atmospheric evaporative demand' s ability to drive water flux is constrained by water supply.

Canopy interception evaporation correlates most strongly with NDVI ($r = 0.83$, $p < 0.001$), with highly overlapping time series, and also correlates significantly with precipitation and specific humidity ($r = 0.45$, 0.42, $p < 0.01$). Interception water originates from discontinuous canopy-precipitation events, requiring less energy due to lower evaporation rates, and thus shows no significant correlation with energy supply or atmospheric demand factors.

2.3.2 Attribution Analysis of Evapotranspiration

Attribution analysis results align with correlation analysis. Transpiration is dominated by NDVI, with an absolute contribution of 28.16%, nearly equal to the other three factors combined (30.93%). Radiation and precipitation also contribute substantially to transpiration (10.25% and 9.31%, respectively). Temperature and wind speed contribute minimally (4.68% and 7.19%) due to vegetation' s biophysical responses that reduce atmospheric demand impacts through stomatal regulation. Evaporation is dominated by temperature (12.01% absolute contribution), with specific humidity and precipitation contributing 9.31% and 4.68%, respectively.

Weighted by each component' s contribution to total evapotranspiration change, the contributions of different factors to overall evapotranspiration were assessed [Figure 6: see original paper]. The results show that known factors explain 71.60% of evapotranspiration variation, with NDVI having the highest explanatory power (28.16% absolute contribution). Vegetation activity not only dominates transpiration (70.09% of total evapotranspiration change) but also dominates canopy interception evaporation (0.57% of total change) through precipitation interception. Additionally, vegetation cover changes affect surface albedo and roughness, influencing evaporation processes.

Temperature ranks second; despite dominating evaporation, its low contribution to total evapotranspiration change (29.34%) limits its absolute contribution to 12.01%. Specific humidity, precipitation, and wind speed contribute 10.25%, 9.31%, and 4.68%, respectively, primarily by altering atmospheric evaporative demand to drive water flux from surface to atmosphere. However, vegetation can mitigate these effects through stomatal control, resulting in lower contributions to transpiration. Due to complementary feedback mechanisms between atmospheric and unsurface water fluxes, the dominant factor in the relationship between atmospheric demand and actual evapotranspiration can shift with changing conditions.

According to Budyko theory, water supply should be the primary limiting factor for evapotranspiration in arid Central Asia. However, precipitation' s absolute contribution is only 4.75%, likely because precipitation is not the sole water source. The region has complex water sourcing mechanisms, with glacier and snowmelt feeding most rivers and representing important freshwater sources. Billions of people depend on meltwater from thousands of Asian high-mountain glaciers. Transpiration, the component contributing most to evapotranspiration change, is a continuous process directly sourced from root-zone soil moisture, which is recharged by discontinuous precipitation. Studies show global evapotranspiration changes are driven by soil moisture variation. Incorporating glacier melt and soil moisture as water sources could further improve explanatory power for evapotranspiration changes in arid Central Asia.

3 Conclusions

This study simulated actual evapotranspiration in arid Central Asia from 2000 to 2020 using the PT-DTsR model and analyzed its spatiotemporal variation and driving factors. The main conclusions are:

1) Evapotranspiration in arid Central Asia increased at 1.45 $\mathrm{mm \cdot a^{-1}}$, showing an east-west spatial pattern. Both evapotranspiration magnitude and trend exhibit summer > spring > autumn > winter characteristics. Evapotranspiration originates from transpiration and evaporation, with mean annual contributions of 36.30% and 63.15%, respectively. Transpiration increased at 2.46 $\mathrm{mm \cdot a^{-1}}$ (68.14% of area), while evaporation decreased at -1.03 $\mathrm{mm \cdot a^{-1}}$ (63.33% of area). Their contributions to total evapotranspiration change were 70.09% and 29.34%, respectively.
2) NDVI is the dominant factor driving evapotranspiration change, with an absolute contribution of 28.16%. Temperature dominates evaporation, while vegetation activity dominates both transpiration and canopy interception evaporation.

References

[1] UNESCO U W. United Nations World Water Development Report 2020: Water and Climate Change[R]. Paris: UNESCO, 2020. [2] Eliasson J. The rising pressure of global water shortages[J]. Nature, 2014, 517(7532): 6. [3] Rijsberman F R. Water scarcity: Fact or fiction?[J]. Agricultural Water Management, 2006, 80(1-3): 5-22. [4] Vörösmarty C J, Mcintyre P B, Gessner M O, et al. Global threats to human water security and river biodiversity[J]. Nature, 2010, 467(7315): 555-561. [5] Li Z, Chen Y, Fang G, et al. Multivariate assessment and attribution of droughts in Central Asia[J]. Scientific Reports, 2017, 7(1): 8. [6] Siegfried T, Bernauer T, Guiennet R, et al. Will climate change exacerbate water stress in Central Asia?[J]. Climatic Change, 2011, 112(3-4): 881-899. [7] Bernauer T, Siegfried T. Climate change and international water conflict in Central Asia[J]. Journal of Peace Research, 2012, 49(1): 227-239. [8] Mao J, Fu W, Shi X, et al. Disentangling climatic and anthropogenic controls on global terrestrial evapotranspiration trends[J]. Environmental Research Letters, 2015, 10(9): 094008. [9] Zhang Y, Peña Arancibia J L, Mcvicar T R, et al. Multi-decadal trends in global terrestrial evapotranspiration and its components[J]. Scientific Reports, 2016, 6(1): 1-12. [10] Fisher J B, Melton F, Middleton E, et al. The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources[J]. Water Resources Research, 2017, 53(4): 2618-2626. [11] Niu Z, He H, Zhu G, et al. An increasing trend in the ratio of transpiration to total terrestrial evapotranspiration in China from 1982 to 2015 caused by greening and warming[J]. Agricultural and Forest Meteorology, 2019, 279: 107701. [12] Pour S H, Wahab A K A, Shahid S, et al. Changes in reference evapotranspiration and its driving factors in peninsular Malaysia[J]. Atmospheric Research, 2020, 246:

105096. [13] Katul G G, Oren R, Manzoni S, et al. Evapotranspiration: A process driving mass transport and energy exchange in the soil-plant-atmosphere climate system[J]. Reviews of Geophysics, 2012, 50(3): RG3002. [14] Mcmahon T A, Finlayson B L, Peel M C. Historical developments of models for estimating evaporation using standard meteorological data[J]. Wiley Interdisciplinary Reviews: Water, 2016, 3(6): 788-818. [15] Budyko M I. The effect of solar radiation variations on the climate of the Earth[J]. Tellus, 1969, 21(5): 611-619. [16] Xu S, Yu Z, Yang C, et al. Trends in evapotranspiration and their responses to climate change and vegetation greening over the upper reaches of the Yellow River Basin[J]. Agricultural and Forest Meteorology, 2018, 263: 118-129. [17] Zeng Z, Peng L, Piao S. Response of terrestrial evapotranspiration to Earth' s greening[J]. Current Opinion in Environmental Sustainability, 2018, 33: 9-25. [18] Yang Z, Zhang Q, Hao X, et al. Changes in evapotranspiration over global semiarid regions 1984-2013[J]. Journal of Geophysical Research: Atmospheres, 2019, 124(6): 2946-2963. [19] Jiang F, Xie X, Liang S, et al. Loess Plateau evapotranspiration intensified by land surface radiative forcing associated with ecological restoration[J]. Agricultural and Forest Meteorology, 2021, 311: 108684. [20] Liu J, You Y. The roles of catchment characteristics in precipitation partitioning within the budyko framework[J]. Journal of Geophysical Research: Atmospheres, 2021, 126(16): e2021JD035168. [21] Piao S, Wang X, Park T, et al. Characteristics, drivers and feedbacks of global greening[J]. Nature Reviews Earth & Environment, 2019, 1(1): 14-27. [22] Chen C, Park T, Wang X, et al. China and India lead in greening of the world through land use management[J]. Nature Sustainability, 2019, 2: 122-129. [23] Zhu Z, Piao S, Myneni R B, et al. Greening of the Earth and its drivers[J]. Nature Climate Change, 2016, 6(8): 791-795. [24] Zeng Z, Piao S, Li Z X, et al. Impact of earth greening on the terrestrial water cycle[J]. Journal of Climate, 2018, 31(7): 2633-2650. [25] Pan S, Tian H, Dangal S R S, et al. Responses of global terrestrial evapotranspiration to climate change and increasing atmospheric CO2 in the 21st century[J]. Earth' s Future, 2015, 3(1): 15-35. [26] Yao J, Chen Y, Chen J, et al. Intensification of extreme precipitation in arid Central Asia[J]. Journal of Hydrology, 2021, 598: 126467. [27] Hao X, Fan X, Zhao Z, et al. Spatiotemporal patterns of evapotranspiration in Central Asia from 2000 to 2020[J]. Remote Sensing, 2023, 15(4): 1150. [28] Yao Y, Liang S, Cheng J, et al. MODIS driven estimation of terrestrial latent heat flux in China based on a modified Priestley-Taylor algorithm[J]. Agricultural and Forest Meteorology, 2013, 171-172: 187-195. [29] Fisher J B, Tu K P, Baldocchi D D. Global estimates of the land-atmosphere water flux based on monthly AVHRR and ISLSCP-II data, validated at 16 FLUXNET sites[J]. Remote Sensing of Environment, 2008, 112(3): 901-919. [30] Cao M, Wang W, Xing W, et al. Multiple sources of uncertainties in satellite retrieval of terrestrial actual evapotranspiration[J]. Journal of Hydrology, 2021, 601: 126642. [31] Teuling A J, Van Loon A F, Seneviratne S I, et al. Evapotranspiration amplifies European summer drought[J]. Geophysical Research Letters, 2013, 40(10): 2071-2075. [32] Yao Y, Wang X, Li Y, et al. Spatiotemporal pattern of gross primary productivity and its covariation with climate in China over the last thirty years[J]. Global Change Biology, 2018, 24(1): 184-196. [33] Jiang L, Guli Jiapaer, Bao A, et al. Vegetation dynamics and responses to climate change and human activities in Central Asia[J]. Science of The Total Environment, 2017, 599-600: 967-980. [34] Zhao R, Liu X, Dong J, et al. Human activities modulate greening patterns: A case study for southern Xinjiang in China based on long time series analysis[J]. Environmental Research Letters, 2022, 17(4): 044012. [35] Budyko M I. The heat balance of the earth' s surface[J]. Soviet Geography, 1961, 2(4): 3-13. [36] Chen Y, Li W, Deng H, et al. Changes in Central Asia' s water tower: Past, present and future[J]. Scientific Reports, 2016, 6: 35458. [37] Bolch T. Hydrology: Asian glaciers are a reliable water source[J]. Nature, 2017, 545(7653): 161-162. [38] Pritchard H D. Asia' s shrinking glaciers protect large populations from drought stress[J]. Nature, 2019, 569(7758): 649-654. [39] Jung M, Reichstein M, Ciais P, et al. Recent decline in the global land evapotranspiration trend due to limited moisture supply[J]. Nature, 2010, 467(7318): 951-954.

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