

## Spatiotemporal Evolution of Atmospheric Water Cycle Elements in the Central Asian Arid Region under Climate Change: Postprint

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### Abstract

Based on reanalysis data, this study systematically analyzes the spatiotemporal variation characteristics of water cycle components including atmospheric water vapor content, water vapor budget, precipitation, and actual evapotranspiration in the arid region of Central Asia from 1979 to 2018. The results show that: (1) Water cycle components in Central Asia exhibit significant spatial heterogeneity. Precipitation and actual evapotranspiration are high-value zones in the Tianshan and Pamir mountains and surrounding oasis areas, and low-value zones in desert plain regions, whereas atmospheric water vapor content shows the opposite pattern. (2) From 1979 to 2018, water vapor content in Central Asia displays a weak decreasing trend with pronounced regional differences in the rate of change: it decreased significantly in the vicinity of the Aral Sea but increased substantially in most of Xinjiang and the Tianshan mountainous region. Water vapor transport in Central Asia is dominated by zonal flow, with relatively weaker meridional transport. The water vapor budget and its variations differ considerably across regions: water vapor transport through the western and northern boundaries decreased, while that through the eastern and southern boundaries increased. The water vapor budget exhibits an increasing trend in northwestern Central Asia, southern Central Asia, the Pamir Plateau, and the Tianshan mountainous region, but a decreasing trend in northern Central Asia and most of Xinjiang. (3) In contrast to changes in water vapor transport, precipitation in Central Asia shows an increasing trend from 1979 to 2018, at a rate of  $4.14 \text{ mm} \cdot (10\text{a})^{-1}$ , with large interannual variability. The significantly increasing trend is found in northern Central Asia, most of Xinjiang, and the Tianshan mountainous region, while a marked decreasing trend occurs in northwestern and southern Central Asia. (4) Actual evapotranspiration in Central Asia shows a weak increasing trend, with significant increases in northern Central Asia, the Tianshan mountainous region, and the Pamir Plateau,

but notable decreases in the Aral Sea region, southern Central Asia, and the arid areas of southern Xinjiang. Seasonally, the spatiotemporal distribution characteristics of seasonal variations in water cycle components are basically consistent with those of annual variations. The research findings contribute to further understanding of the evolution and mechanisms of atmospheric water cycling in the arid region of Central Asia. Key

## Full Text

### Preamble

#### Spatiotemporal Evolution of Atmospheric Water Cycle Elements in the Arid Regions of Central Asia Under Climate Change

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**Abstract:** Based on reanalysis data, this study systematically analyzes the spatiotemporal variation characteristics of atmospheric water vapor content, water vapor budget, precipitation, and actual evaporation in the arid regions of Central Asia from 1979 to 2018. The results reveal significant spatial heterogeneity in water cycle elements across Central Asia. Precipitation and actual evaporation exhibit high values in mountainous areas such as the Tianshan and Pamir Mountains and surrounding oasis regions, while showing low values in desert plains; atmospheric water vapor content displays the opposite pattern. From 1979 to 2018, water vapor content in Central Asia shows a weak decreasing trend with notable regional differences in change rates, decreasing significantly around the Aral Sea while increasing markedly in most of Xinjiang and the Tianshan Mountains. Zonal transport dominates water vapor transport in Central Asia, with relatively weak meridional transport. Water vapor budgets and their changes vary considerably across regions, with decreasing transport through western and northern boundaries and increasing transport through eastern and southern boundaries. Water vapor budgets show increasing trends in northwestern Central Asia, southern Central Asia, the Pamir Plateau, and Tianshan Mountains, but decreasing trends in northern Central Asia and most of Xinjiang. In contrast to changes in water vapor transport, precipitation in Central Asia increased during 1979–2018 at a rate of  $4.14 \text{ mm } (10\text{a})^{-1}$ , with substantial interannual variability. Significant increasing trends occur in northern Central

Asia, most of Xinjiang, and the Tianshan Mountains, while significant decreasing trends appear in northwestern and southern Central Asia. Actual evaporation shows a slight increasing trend, with notable increases in northern Central Asia, the Tianshan Mountains, and the Pamir region, but significant decreases in the Caspian Sea area, Aral Sea, southern Central Asia, and southern Xinjiang. Seasonally, the spatial distribution patterns of water cycle elements in each season are generally consistent with annual patterns. These findings enhance understanding of atmospheric water cycle evolution and mechanisms in the arid regions of Central Asia.

**Keywords:** Central Asian arid region; water cycle; water vapor content; precipitation; actual evaporation; water vapor budget

## Introduction

The arid regions of Central Asia, located in the hinterland of the Eurasian continent, represent the world's largest non-zonal arid area and constitute a critical upstream region influencing China's weather and climate, with significant impacts on disastrous weather occurrence and regional climate change in northwestern and eastern China. Water resource shortages are particularly acute in Central Asian arid regions, with only a small fraction of freshwater resources being utilizable. The ecological environment is fragile, making it one of the most sensitive regions to global climate change. Global warming directly affects the stability of regional water cycles, altering runoff recharge patterns and water resource quantities, thereby increasing uncertainty in water resource spatiotemporal distribution. Climate change and human activities have also caused declining lake water levels, shrinking areas, and deteriorating water quality in Central Asia. As global temperatures rise, atmospheric water cycle processes in arid regions intensify, with both precipitation and evaporation increasing significantly, leading to changes in water cycle structure and distribution.

Precipitation is the source of all terrestrial water resources and can be considered the upper limit of water resources in a region. Water vapor is the primary prerequisite for precipitation formation, and understanding the material basis of water vapor is key to addressing precipitation processes. The complex mountain-basin topography of Central Asian arid regions, with numerous large mountains in the south blocking warm and moist airflows, allows only weak, cool, and humid water vapor carried by the upper-level westerlies to reach the region, forming the distinct "westerly pattern" characteristic of Central Asia. Previous studies using different drought indices to assess global land dryness changes suggest rapid aridification of global land areas, with particularly evident drying trends in central and southern Central Asia.

Precipitation, evaporation, and water vapor transport constitute the atmospheric branch of the water cycle process, determining the total water resources of a region. Atmospheric water vapor content in arid regions is influenced by geographical latitude, terrain elevation, and atmospheric circulation, with

lower values compared to mid- and low-latitude regions. Research has found that water vapor distribution over Central Asian arid regions generally exhibits the pattern of “more in the south, less in the north; more in the west, less in the east; more in plains, less in mountains.” Central Asian precipitation shows complexity, with significant increases during cold seasons. Water vapor transport, as a crucial link connecting precipitation and evaporation processes to form a complete water cycle, demonstrates pronounced seasonal differences in Central Asian arid regions, with zonal water vapor input and meridional output in winter, and water vapor output in both zonal and meridional directions in summer. Water vapor changes are affected by multiple factors, with large-scale atmospheric circulation and elevation influencing annual average water vapor pressure in arid regions.

Previous studies often treated Central Asian arid regions as a single entity when analyzing precipitation changes, water vapor distribution, and transport characteristics, despite significant spatial differences in atmospheric water cycle components. This paper divides Central Asian arid regions into eight climate subregions and examines spatiotemporal evolution characteristics of three elements—water vapor content and budget, precipitation, and actual evaporation—using multiple reanalysis datasets to explore regional differences in atmospheric water cycle structure. This approach will enhance understanding of atmospheric water cycle evolution in Central Asian arid regions and further analyze the influence mechanisms of internal water vapor transport.

## 1. Data and Methods

### 1.1 Data Description

This study utilizes the following datasets: (1) Monthly precipitation data from the Global Precipitation Climatology Centre (GPCC) at  $0.25^\circ \times 0.25^\circ$  resolution; (2) Monthly total column water vapor content and actual evaporation reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 at  $0.25^\circ \times 0.25^\circ$  resolution; (3) ERA-Interim reanalysis data to calculate water vapor budgets for each subregion boundary in Central Asia from 1979 to 2018. Studies indicate that ERA5 is more suitable than other reanalysis datasets for investigating spatiotemporal distribution of atmospheric precipitable water in Central Asia. Due to significant spatial climate differences in Central Asian arid regions, analysis of water cycle structure requires differentiation by climate subregion.

This study employs the Köppen climate classification system, which classifies climates based on temperature, precipitation, and vegetation types, to divide Central Asian arid regions into eight climate subregions [Figure 1: see original paper]. The classification considers: (1) Spatial distribution of multi-year average precipitation and annual precipitation cycles; (2) Topographic and geomorphological features including mountains, deserts, plateaus, plains, basins, hills, and valleys. The resulting eight subregions are: Northwestern Central Asia

(CWA), Northern Central Asia (CNA), Southern Central Asia (CSA), Pamir-Western Tianshan (PWT), Northern Xinjiang (NXJ), Southern Xinjiang (SXJ), Central Tianshan (CTS), and Eastern Tianshan (ETS) .

## 1.2 Climate Zoning of Central Asia

Central Asian arid regions exhibit complex and diverse climate types with distinct characteristics. Northwestern Central Asia features hills and lowlands with arid desert and steppe climates under the Köppen system, with annual average temperature below 10°C and relatively uniform seasonal precipitation. Northern Central Asia includes central Kazakhstan with hilly underlying surfaces, where precipitation peaks in summer. Southern Central Asia and Southern Xinjiang are both desert regions; Southern Central Asia's Turkmenistan and Uzbekistan have Mediterranean-like climates with low summer precipitation, though more humid than the Tarim Basin in Southern Xinjiang. The Pamir-Western Tianshan region, with high elevation, experiences combined Mediterranean and plateau climates with abundant precipitation concentrated in winter and spring. Northern Xinjiang has a temperate grassland climate with summer-focused precipitation. Central and Eastern Tianshan, though both mountainous, differ significantly in climate: Central Tianshan receives more precipitation, while Eastern Tianshan is extremely arid with multi-year average precipitation below 100 mm.

## 2. Results and Analysis

### 2.1 Spatial Distribution and Variation Characteristics of Atmospheric Water Vapor Content

**2.1.1 Spatial Distribution of Atmospheric Water Vapor Content** Total column atmospheric water vapor content in Central Asian arid regions shows substantial spatial differences, decreasing from Turkmenistan in the southwest toward higher latitudes in the northeast [Figure 2a: see original paper]. Influenced by terrain, water vapor content is high along the Tianshan and Kunlun Mountains, exceeding 14 mm, while low values occur in the low-altitude basin area between the Caspian Sea and Aral Sea. From a trend perspective [Figure 2b: see original paper], total column water vapor content in Central Asia during 1979–2018 shows a weak decreasing trend of  $-0.01 \text{ mm (10a)}^{-1}$ , with significant regional variation rates. Using a boundary from west of Lake Balkhash to the mountainous area southeast of Uzbekistan, water vapor content shows opposite trends of “increase in the east, decrease in the west.” The most significant decrease occurs in the Aral Sea region, reaching below  $-0.2 \text{ mm (10a)}^{-1}$ , while water vapor content in the Kunlun and Tianshan Mountains of Southern Xinjiang shows significant increases.

Interannual variation dominates the total column atmospheric water vapor content in Central Asia during 1979–2018 [Figure 2c: see original paper], with no significant long-term trend. Water vapor content fluctuations were relatively

small before 2000 but increased around 2000.

From a subregional perspective, Southern Central Asia has the highest water vapor content, followed by Northwestern and Northern Central Asia, while Central Tianshan, Southern Xinjiang, and Pamir-Western Tianshan have lower values. In terms of trends, the first five subregions show decreasing water vapor content, with Southern Central Asia showing the largest decrease at  $-0.12 \text{ mm (10a)}^{-1}$ . Other subregions show varying degrees of increase, with Eastern Tianshan showing the largest increase at  $0.10 \text{ mm (10a)}^{-1}$ , followed by Southern Xinjiang and Eastern Tianshan.

The seasonal distribution and variation trends of water vapor content show a “high in summer, low in winter, similar in spring and autumn” pattern [Figure 3: see original paper]. Due to topographic effects, mountainous areas have significantly lower water vapor content than basins. Total column water vapor content includes the sum of water vapor, liquid water, cloud ice, rain, and snow from the surface to the top of the atmosphere. In plains, valleys, and basins, the air column is thicker, resulting in larger atmospheric water vapor content values; in plateau and mountainous areas with higher terrain, the thinner air column yields smaller values, consistent with findings by Shi et al. [27]. Although mountainous areas have lower water vapor content than plains, dynamic conditions are crucial for precipitation formation. In arid regions, precipitation conversion efficiency is higher in mountains than in basins, creating the inverse distribution pattern between precipitation/evaporation and atmospheric water vapor content [28].

Seasonal analysis reveals significant differences in water vapor change rates across seasons [FIGURE:3e–h]. In spring, most of Central Asia shows increased total column water vapor content, while Southern Xinjiang shows a weak decreasing trend [Figure 3e: see original paper]. Summer water vapor changes are dominated by decreases [Figure 3f: see original paper], generally showing an “east increase, west decrease” pattern, with significant decreases in the Caspian Sea-Aral Sea region and significant increases north of the Kunlun Mountains and in the Tianshan Mountains. Autumn water vapor shows a “south increase, north decrease” trend [Figure 3g: see original paper], with significant decreases in the Caspian Sea-Aral Sea region and increases in lower-latitude Southern Xinjiang; water vapor content north of Lake Balkhash and in Northern Xinjiang shifts from summer increase to autumn decrease. In winter, decreases dominate, with significant reductions in Northern Xinjiang’s Altai Mountains region [Figure 3h: see original paper].

Western Central Asia receives water vapor mainly through mid-latitude prevailing westerlies associated with deep Central Asian troughs, while Xinjiang is also influenced by various monsoon circulation patterns. The weakening of westerlies since the 1980s, with the regional westerly index showing a decreasing trend of  $-0.25 \times 10^{-1} \text{ hPa (10a)}^{-1}$ , has reduced water vapor carried by westerly systems to Central Asia, potentially causing decreasing water vapor trends in western Central Asia [29]. Weakened westerlies favor East Asian and In-

dian monsoons transporting water vapor to Xinjiang, though autumn monsoon bursts are weaker than summer ones, potentially leading to reduced autumn water vapor in Xinjiang compared to summer.

**2.2.1 Water Vapor Budget at Subregional Boundaries** Analysis of water vapor budgets at subregional boundaries reveals large differences across Central Asia [Figure 4: see original paper]. Overall, zonal water vapor transport exceeds meridional transport, with the western boundary serving as the main water vapor input and the southern boundary providing relatively weak input; northern boundary water vapor output is weaker than eastern boundary output.

From a subregional perspective, Northwestern Central Asia is a multi-year average water vapor sink with net water vapor income of  $0.59 \times 10^9 \text{ kg s}^{-1}$ , where eastern boundary output is less than western boundary input, and southern boundary input is less than northern boundary output, resulting in a water vapor convergence zone with decreasing multi-year water vapor input. Northern Central Asia is dominated by zonal water vapor transport with weak meridional transport, and total water vapor budget at each boundary is roughly equivalent. Southern Central Asia differs as a multi-year average water vapor source region, with decreasing zonal water vapor transport and increasing water vapor output at both north and south boundaries. The Pamir-Western Tianshan region has higher water vapor input at western and southern boundaries than output at eastern and northern boundaries, making it a weak water vapor convergence zone with an increasing trend. Both Northern Xinjiang and Central Tianshan are water vapor source regions with only western boundary input; Northern Xinjiang is dominated by zonal transport, while Central Tianshan has stronger meridional output. Eastern Tianshan has a multi-year average water vapor budget of  $-0.25 \times 10^9 \text{ kg s}^{-1}$ , representing a water vapor divergence zone throughout the year, with meridional transport exceeding zonal transport, decreasing water vapor input at western and northern boundaries, and increasing output at eastern and southern boundaries, forming a decreasing trend in multi-year water vapor divergence. Southern Xinjiang differs, with water vapor input at all boundaries except the eastern one; decreasing input combined with increasing eastern boundary output leads to a decreasing trend in multi-year water vapor convergence.

## 2.2 Precipitation

**2.2.1 Spatial Distribution of Precipitation** Annual precipitation in Central Asia is extremely unevenly distributed [Figure 5a: see original paper], with a multi-year average of 265.2 mm. Southern Xinjiang and Southern Central Asia receive less than 100 mm, while a precipitation maximum center appears in the Pamir-Western Tianshan region, locally exceeding 550 mm. Central Tianshan receives the second-highest precipitation, followed by Northern Central Asia, Northern Xinjiang, and Northwestern Central Asia, all exceeding 200 mm. The desert area of Southern Xinjiang has scarce precipitation, with a multi-year

average of only 67.5 mm.

Seasonal precipitation differences are significant [FIGURE:6a-d]. The Pamir-Western Tianshan region has precipitation concentrated in winter and spring, higher than other regions. The lowest precipitation values in summer occur in Southern Central Asia, while in the other three seasons they occur in Southern Xinjiang. Northern Xinjiang and Northern Central Asia have summer-dominated precipitation, with similar spring and autumn distributions and the lowest precipitation in winter. Precipitation in Northwestern Central Asia increases with latitude, particularly evident in summer.

**2.2.2 Temporal Variation of Precipitation** Precipitation in Central Asia increased slightly during 1979–2018 at a rate of  $4.14 \text{ mm } (10\text{a})^{-1}$  [Figure 5b: see original paper], with large interannual fluctuations and a slow upward trend after 2000 [Figure 5c: see original paper]. Precipitation change rates show decreasing trends in Northwestern and Southern Central Asia, while other regions show increasing trends [Figure 5b: see original paper]. Central Tianshan shows the largest increase at  $12.99 \text{ mm } (10\text{a})^{-1}$ , followed by Eastern Tianshan at  $11.09 \text{ mm } (10\text{a})^{-1}$  and Northern Xinjiang at  $8.72 \text{ mm } (10\text{a})^{-1}$ .

Seasonal precipitation variations also differ across seasons. Most of Central Asia shows increasing spring precipitation, while Southern Central Asia and the Pamir-Western Tianshan region show decreases [Figure 6e: see original paper]. Summer precipitation decrease expands to Northwestern Central Asia, though few areas pass significance tests, while Northern Xinjiang, Central Tianshan, and the western Tarim Basin show large precipitation increases [Figure 6f: see original paper]. In autumn [Figure 6g: see original paper], Northwestern Central Asia, Pamir-Western Tianshan, and Eastern Tianshan show precipitation decreases, with significant areas in Kazakhstan's Turgay Plateau, while other regions show increasing trends. In winter [Figure 6h: see original paper], Northwestern Central Asia, Xinjiang, and areas near Lake Balkhash show precipitation increases, while other regions show decreasing trends.

## 2.3 Actual Evaporation

**2.3.1 Spatial Distribution of Actual Evaporation** Evaporation constitutes an important component of the water cycle. Figure 7a shows the spatial distribution of average evaporation across Central Asia, with significant differences among subregions. Northern Central Asia has the highest evaporation, exceeding 400 mm, related to the lake underlying surface in this region. The Pamir-Western Tianshan region has higher evaporation than surrounding areas, with some regions above 400 mm. Influenced by terrain, high evaporation zones are mainly located in oasis areas on both sides of mountains and around rivers and lakes, with evaporation on both sides of Xinjiang's mountains higher than in basins. The extremely arid eastern Tarim Basin has evaporation below 100 mm.

Seasonal evaporation is primarily concentrated in summer, followed by spring and autumn, with the lowest values in winter. In spring [Figure 8a: see original paper], evaporation is highest in the Pamir-Western Tianshan region, with Northern and Northwestern Central Asia higher than Southern Central Asia. Northern Xinjiang's evaporation exceeds Southern Xinjiang's, with basin evaporation in Southern Xinjiang lower than in Northern Xinjiang. The Pamir-Western Tianshan region's evaporation can reach up to 240 mm. In summer [Figure 8b: see original paper], evaporation is significantly higher than in other seasons, exceeding 24 mm in most of Central Asia except high mountainous areas, particularly near the Caspian Sea coast. Autumn evaporation [Figure 8c: see original paper] is slightly lower than spring but shows similar spatial patterns. Winter evaporation [Figure 8d: see original paper] is significantly lower than other seasons, with most regions except Southern Central Asia having evaporation below 20 mm.

**2.3.2 Variation Characteristics of Actual Evaporation** Actual evaporation in Central Asia shows a weak increasing trend of  $2.11 \text{ mm } (10\text{a})^{-1}$  [Figure 7b: see original paper], with a slight upward fluctuation after 2000 [Figure 7c: see original paper]. Northwestern Central Asia shows a decreasing trend that passed the 0.05 significance test, while Southern Central Asia shows increasing evaporation; Northern Central Asia's increasing trend reaches  $8.63 \text{ mm } (10\text{a})^{-1}$ . Xinjiang shows an overall decreasing trend, with significant decreases in Southern Xinjiang [Figure 7b: see original paper].

Evaporation trends vary by season [FIGURE:8e-h]. Northwestern Central Asia shows decreasing evaporation in summer and autumn and increasing evaporation in winter and spring. Northern Central Asia shows significant increasing trends in winter and spring, with the decreasing area expanding in autumn. Southern Central Asia shows an overall decreasing trend, except in Turkmenistan where only winter shows a decreasing trend. The Pamir-Western Tianshan region shows increasing trends in spring, summer, and autumn, while Eastern Tianshan shows positive trends in all four seasons. Except for winter, Southern Xinjiang shows decreasing evaporation trends, while the Tarim River and northeastern Southern Xinjiang show significant increasing trends in winter.

Actual evaporation is the dominant variable controlling water vapor recycling, and its changes in Central Asia are mainly controlled by precipitation variations [36]. Precipitation directly affects surface soil moisture, thereby influencing actual evaporation. Winter precipitation in Southern Xinjiang shows an increasing trend, while other seasons show varying degrees of decrease. Additionally, actual evaporation is strongly influenced by underlying surface conditions; changes in soil moisture and surface cover in the Tarim River basin may also contribute to increasing evaporation trends in winter around the Tarim River and its northeastern areas.

## 2.4 Atmospheric Water Cycle Structure in Central Asian Arid Regions

Atmospheric water cycles differ significantly across Central Asian regions during 1979–2018 [Figure 9: see original paper]. High atmospheric water vapor content occurs in plains and basins, while mountainous areas with higher elevation show low values, whereas precipitation and evaporation show the opposite pattern. Desert basins have thicker air columns than plateau mountainous areas, resulting in higher water vapor content. Due to lack of dynamic conditions, precipitation conversion efficiency in basins is lower than in mountains, creating the characteristic distribution where precipitation and evaporation differ from atmospheric water vapor content in Central Asian arid regions.

In Northwestern Central Asia, multi-year average atmospheric water vapor content is 13.7 mm, higher than most other Central Asian regions. Annual water vapor input is less than output, with annual surface evaporation reaching 403.6 mm, about double the annual precipitation of 248.1 mm. The relatively humid underlying surface of the Caspian Sea coastal lowlands provides favorable conditions for high evaporation in this region. Northern Central Asia has lower atmospheric water vapor content than Northwestern Central Asia, with roughly equivalent annual water vapor input and output values, both higher than in Northwestern Central Asia. Annual surface evaporation is about half of annual precipitation.

Southern Central Asia has the lowest terrain and the highest atmospheric water vapor content in Central Asia at 15.0 mm, with annual water vapor input lower than output and annual precipitation only half of annual surface evaporation at 182.3 mm. The underlying surface is mostly desert, with precipitation decreases and evaporation increases, particularly in eastern Turkmenistan, where drought-induced vegetation and land degradation exacerbate precipitation demand and further deteriorate the local water cycle [38].

The Pamir-Western Tianshan region has relatively abundant precipitation, with multi-year average precipitation exceeding 350 mm, atmospheric water vapor content of 8.6 mm, and significantly lower water vapor transport than the first three regions, with annual surface evaporation and annual precipitation being relatively close. Glaciers are important sources of surface runoff in Central Asia, and the Pamir-Western Tianshan region, as an important water source area for Central Asian arid regions, experiences glacier retreat that affects surface runoff and has extremely adverse effects on local atmospheric water cycle processes [39].

Xinjiang, located downstream of the Central Asian westerly belt, has lower atmospheric water vapor content than upstream areas. Its water vapor is influenced by various monsoon circulation patterns, with multi-year water vapor transport lower than other Central Asian regions [21]. Northern Xinjiang has multi-year average atmospheric water vapor content of 9.2 mm, with water vapor transport magnitude comparable to the Pamir-Western Tianshan region. Annual water vapor input is less than output, with annual surface evaporation about 80

mm higher than annual precipitation. Central and Eastern Tianshan have relatively low water vapor transport; Central Tianshan's annual water vapor input is only  $0.90 \times 10^9 \text{ kg s}^{-1}$ , indicating that local water vapor recycling may contribute more to precipitation than external water vapor transport. Central Tianshan's annual surface evaporation and precipitation both exceed 300 mm, while Eastern Tianshan's annual evaporation is 185.2 mm and annual precipitation is less than 100 mm.

Southern Xinjiang has lower atmospheric water vapor content of about 8.4 mm, with annual output water vapor about half of input and annual evaporation reaching 201.2 mm, while annual precipitation is very small at only 67.5 mm, far lower than Northern Xinjiang. The large precipitation difference between Northern and Southern Xinjiang results from multiple factors. Studies show that spring thermal anomalies over the Tibetan Plateau affect large-scale circulations such as the subtropical westerly jet and South Asian high, regulating summer precipitation changes in Northern Xinjiang [40]. When the Tibetan Plateau's sensible heat is weak and the desert to its northwest has strong sensible heat, southerly winds prevail over Xinjiang, with an anticyclonic circulation over the Arabian Sea cooperating with a cyclonic circulation over Central Asia to further transport tropical water vapor to Northern Xinjiang, causing above-normal summer precipitation there [41].

Atmospheric warming and humidification will enhance the atmospheric water cycle in Central Asian arid regions. However, inconsistent responses to climate change across different subregions affect the water cycle process to varying degrees. Additionally, as an important component of the atmospheric water cycle, actual evaporation lacks observational data, and its estimation relies heavily on models, adding uncertainty to water cycle structure analysis.

### 3. Conclusions

The atmospheric water cycle process in Central Asian arid regions is unique, with significant spatial differences in atmospheric water vapor content, water vapor budget, precipitation, and actual evaporation. Precipitation and actual evaporation show distributions opposite to atmospheric water vapor content, with high values in mountainous areas such as the Tianshan and Pamir Mountains and surrounding oasis regions, and low values in desert plains due to elevation effects. Based on multiple reanalysis datasets, this study analyzes variation characteristics of atmospheric water cycle elements in Central Asia, with main conclusions as follows:

- 1) From 1979 to 2018, water vapor content change rates show obvious regional differences in Central Asian arid regions, with significant decreases in the Caspian Sea-Aral Sea region in western Central Asia, but significant increases in most of Xinjiang and the Tianshan Mountains. Water vapor transport in Central Asian arid regions is dominated by zonal transport, with large differences in water vapor budgets and changes across

regions. Unlike the decreasing trends in Northern Central Asia and most of Xinjiang, water vapor budgets show increasing trends in Northwestern Central Asia, Southern Central Asia, the Pamir region, and the Tianshan Mountains.

- 2) Precipitation in Central Asian arid regions shows an increasing trend with large interannual fluctuations, increasing by 3.76% after 2000. Significant increasing trends occur in Northern Central Asia, most of Xinjiang, and the Tianshan Mountains, while Northwestern and Southern Central Asia show significant decreasing trends.
- 3) Actual evaporation shows a slight increasing trend, with significant increases in Northern Central Asia, the Tianshan Mountains, and the Pamir region, but significant decreases in the Caspian Sea area, Aral Sea, Southern Central Asia, and Southern Xinjiang. Seasonal variations of water cycle elements are generally consistent with annual variation patterns.

Overall, annual surface evaporation exceeds annual precipitation in all subregions of Central Asian arid regions. This phenomenon may result from multiple factors, as evaporation is strongly influenced by underlying surface conditions, surface runoff, and plant transpiration. Limited monitoring data constrain understanding of atmospheric water cycle processes and their changes in Central Asian arid regions. Furthermore, under global warming, the water cycle in Central Asia will undergo a series of changes, and the mechanisms of climate change impacts on Central Asian water cycles require further research. This study only discusses spatiotemporal evolution characteristics of atmospheric water cycle elements in Central Asian arid regions. Since these elements are not independent, their interactions and quantitative contributions to the arid region atmospheric water cycle remain unanalyzed. Future work should strengthen analysis of internal water vapor transport mechanisms and fundamental causes of significant differences in water cycles within arid regions.

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