Variation Characteristics of Atmospheric and Surface Water Resources in Xinjiang (Postprint)

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Abstract

Atmospheric precipitation is the fundamental source of all water resources in Xinjiang, atmospheric water resources constitute the material basis for atmospheric precipitation, and atmospheric precipitation forms surface water resources locally. Water resource shortage is the most critical natural factor constraining high-quality economic and social development and ecological security assurance in Xinjiang. This paper analyzes the variation characteristics of atmospheric water resources and surface water resources in Xinjiang, which holds important scientific significance for the systematic planning and efficient utilization of water resources in Xinjiang. The results show: from 1961 to 2022, the annual precipitation resource amount in Xinjiang was 2717.12$\times 108m^{\{3\}, thewatervaporinputwas 21115\times 108m}\{3\}, thenetwatervaporbudgetwas 347.5\times 108m^{\{3\}, andthewaterv}$ and the water yield coefficient was 0.32. In terms of variation trends, from 1961 to 2022, annual precipitation in Xinjiang increased significantly, total water vapor input and total output over Xinjiang decreased slightly, net water vapor budget increased slightly, and water vapor precipitation efficiency increased significantly; from 2001 to 2021, surface water resources in Xinjiang were in an abundant water period, but the water yield coefficient showed a slight fluctuating decreasing trend. Water resource issues in Xinjiang remain prominent, with insufficient research on refined characteristics of different water resources and transformation relationships between water bodies of different phases; future research needs to be strengthened to address potential water resource security risks in Xinjiang brought by climate change.

Full Text

Change in Atmospheric and Surface Water Resources in Xinjiang

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Abstract

The scarcity of water resources is the most critical natural factor impeding high-quality economic and social development and ecological security in Xinjiang. This paper systematically analyzes trends in precipitation, atmospheric water resources, and surface water resources in Xinjiang, and establishes the conversion relationship between different water resources. The findings reveal that annual precipitation water resources amount to 2717.12$×10^{8}$ m^3, with water vapor input reaching 21115$×10^{8}$ m^3, resulting in a net water vapor income of 347.5$×10^{8}$ m^3. Between 1961 and 2022, Xinjiang experienced a 12.5% increase in precipitation conversion efficiency. The annual total water resources in Xinjiang is 912.3$×10^{8}$ m^3, where surface water resources constituted 864.1$×10^{8}$ m^3 from 2001 to 2020, resulting in a water yield coefficient of 0.32. The observed trends show a significant increase in annual precipitation in Xinjiang, a slight decrease in total water vapor input, a marginal increase in net water vapor income, and a significant increase in precipitation conversion efficiency between 1961 and 2022. Although surface water resources in Xinjiang are abundant, the water yield coefficient exhibited a weak fluctuating decreasing trend from 2001 to 2020. Nevertheless, prominent issues persist in water resources research in Xinjiang, including insufficient studies on precipitation water resource volumes, understanding of cloud water resource characteristics, and continuous monitoring of the physical processes of cloud precipitation. To address these challenges, it is imperative to conduct comprehensive scientific field experiments on cloud precipitation physics, including strengthening research on the physical processes of cloud precipitation, refining cloud water resource assessments, and examining precipitation efficiency and water increase effects within typical cloud systems. These studies will aid in developing cloud water resources and air-groundwater resources joint control technology for arid areas.

Keywords: atmospheric water resource; surface water resource; water yield coefficient; change; Xinjiang

1. Introduction

Xinjiang is a typical arid and semi-arid region with extremely uneven water resource distribution, where the contradiction between economic development and water scarcity is increasingly prominent. Water resources constitute a critical element constraining Xinjiang' s economic and social development, as well as ecological and environmental protection, and have consistently attracted widespread attention from government and society. Atmospheric precipitation, river water, lake water, and groundwater are the primary sources of water utilization in Xinjiang, with alpine glaciers and seasonal snow playing important regulatory roles in the region' s water resources. Atmospheric precipitation resources are the fundamental recharge source for all types of water resources in Xinjiang, while atmospheric water vapor resources provide the material basis for precipitation. Under the background of continuous global warming, Xinjiang' s regional water cycle has intensified, the interannual variability of water vapor and precipitation resources has increased, and uncertainties regarding future water resources in Xinjiang have become more pronounced. Therefore, studying the distribution, evolution characteristics, and patterns of atmospheric water vapor and precipitation resources is fundamental to the scientific development and utilization of atmospheric water resources, and provides an important scientific basis for implementing atmospheric water resource development projects.

Atmospheric water cycling plays a crucial role in climate and global change research. Water vapor transport is an important link in atmospheric water substance and water cycling, while atmospheric water vapor and cloud water are the most active elements and significantly influence energy conversion in the climate system. Global warming has profoundly impacted Xinjiang's water cycling system and water resources. Climate change has altered water cycle structures, exacerbating the variability of key water cycle elements and precipitation resource quantities in Xinjiang, and intensifying the contradiction between water resource issues and the water demands of high-quality development. Previous studies have predominantly analyzed water resources from single aspects, while comprehensive analyses of precipitation resources, atmospheric water resources, and surface water resources in Xinjiang remain limited. Therefore, this study systematically analyzes the basic characteristics and changing trends of atmospheric water vapor, precipitation, and surface water resources in Xinjiang based on the latest ERA-5 reanalysis data, observational data, and publicly released Xinjiang Water Resources Bulletin data, providing scientific support for water resource security and water development in the construction of the "Silk Road Economic Belt."

2. Methods and Data

2.1 Water Vapor Transport Calculation This study utilizes ERA-5 monthly data from the European Centre for Medium-Range Weather Forecasts for the period 1961–2020 to calculate water vapor budget changes in the Xinjiang region and evaluate atmospheric water vapor resources and their variations. Liu et al. confirmed that ERA-5 reanalysis data demonstrate excellent applicability for atmospheric water vapor research in Xinjiang and can be used to analyze atmospheric water vapor changes.

Water vapor flux (Q) represents the mass of water vapor flowing through a unit area per unit time, reflecting the intensity of water vapor transport. The calculation formula for water vapor transport flux is:

$$Q = -\frac{1}{g}\int_{P_s}^{P_z} q \cdot V_n \, dp$$

where g is gravitational acceleration (9.8 $\mathrm{m \cdot s^{-2}}$), q is specific humidity ($\mathrm{g \cdot kg^{-1}}$), P_s is surface pressure (hPa), P_z is atmospheric top pressure (hPa), and V_n is the wind speed component perpendicular to the regional boundary (u, v) ($\mathrm{m \cdot s^{-1}}$). Since water vapor transport is mainly concentrated in the lower atmosphere, the integration is performed from 1000 hPa to 500 hPa.

When calculating water vapor flux across Xinjiang's boundaries, the water vapor fluxes at each boundary are:

Western boundary:

$$Q_\lambda(i)_W = \sum_{i=1}^{m} Q_\lambda(i)$$

Eastern boundary:

$$Q_\lambda(i)_E = \sum_{i=1}^{m} Q_\lambda(i)$$

Southern boundary:

$$Q_\phi(i)_S = \sum_{i=1}^{n} Q_\phi(i)$$

Northern boundary:

$$Q_\phi(i)_N = \sum_{i=1}^{n} Q_\phi(i)$$

where Q_λ and Q_ϕ represent zonal and meridional water vapor fluxes, respectively; Q is the net water vapor flux through the Xinjiang region; i is the grid point index, where m represents the number of grid points on the western and eastern boundaries, and n represents the number of grid points on the northern and southern boundaries; and d is the grid spacing. A negative water vapor flux across a boundary indicates water vapor output, while a positive value indicates water vapor input.

2.2 Data Sources Precipitation observation data from 105 conventional meteorological stations in Xinjiang were obtained from the Xinjiang Meteorological Information Center. Annual precipitation water resources, total water resources, and surface water resources for Xinjiang from 2001 to 2021 were derived from the *Xinjiang Water Resources Bulletin*. Multi-year average total water resources data for Xinjiang (788.7$×10^{8}$ $\mathrm{m^3}$ for 1956-2000 and 832.7$×10^{8}$ $\mathrm{m^3}$ for 1956-2016) were obtained from published literature. Xinjiang population data were sourced from the *China Statistical Yearbook*, with population figures current as of the end of 2021. Xinjiang comprises 14 prefecture-level cities/autonomous prefectures and 4 county-level cities directly under the autonomous region. This study separately calculated precipitation water resources for Shihezi City, while other county-level cities were merged with their respective prefectures: Aral City with Aksu Prefecture, Wujiaqu City with Changji Prefecture, and Tumushuke City with Kashgar Prefecture.

3. Results and Analysis

3.1 Precipitation Changes From 1961 to 2022, the multi-year average annual precipitation in Xinjiang was 198.3 mm, with the Tianshan Mountains receiving the most abundant precipitation at 348.4 mm, followed by northern Xinjiang at 163.2 mm, while southern Xinjiang received scarce precipitation at only 63.2 mm. In terms of trends, annual precipitation in Xinjiang showed an increasing trend at a rate of 8.5 mm $\cdot$ $(10a)^{-1}$. Regionally, the Tianshan Mountains exhibited the highest humidification rate at 14.3 mm $\cdot$ $(10a)^{-1}$, followed by northern Xinjiang at 9.9 mm $\cdot$ $(10a)^{-1}$, while southern Xinjiang showed the smallest increase at 4.9 mm $\cdot$ $(10a)^{-1}$. Generally, regions with higher precipitation experienced greater humidification rates, and vice versa.

From an interdecadal perspective, Xinjiang' s precipitation underwent a significant increase around 1987. Precipitation during 1988-2022 increased by 33.2 mm compared to 1961-1987, representing a 22.7% increase. Regionally, precipitation in northern Xinjiang and the Tianshan Mountains during 1988-2022 increased by 51.8 mm and 39.7 mm, respectively (increases of 40.6% and 16.3%), while southern Xinjiang precipitation increased by 20 mm (a 39.7% increase). In absolute terms, the Tianshan Mountains showed the largest interdecadal humidification, followed by northern and southern Xinjiang; however, in percentage terms, southern Xinjiang exhibited the most pronounced humidification, followed by northern Xinjiang and the Tianshan Mountains. Notably, the interannual variability during 1988-2022 was greater than during 1961-1987. For example, 1997 was the year with the least precipitation in the Tianshan Mountains, while 1998 was the second wettest year on record; 2010 was the wettest year in southern Xinjiang, with precipitation 2.3 times that of 1985, while 2016 was the wettest year in northern Xinjiang and the Tianshan Mountains.

3.2 Precipitation Water Resources The multi-year average annual precipitation water resources in Xinjiang from 1961 to 2022 were 2717.12$×10^{8}$ m^3. Xinjiang' s annual precipitation water resources rank among the lowest nationally, accounting for only 3% of the national total. Per capita annual precipitation water resources are relatively high at 10.5$×10^{3}$ m^3, approximately 1.4 times the national average. However, significant regional disparities exist. The Altay Prefecture, Bayingolin Mongol Autonomous Prefecture (hereafter "Bayingolin"), and Kizilsu Kirghiz Autonomous Prefecture (hereafter "Kizilsu") have abundant per capita precipitation water resources at 30.5$×10^{3}$ m^3, 3.8 times the national average. In contrast, Kashgar Prefecture, Karamay City, Urumqi City, and Shihezi City remain below the national average, with Urumqi reaching only 45.3% of the national level.

Xinjiang' s precipitation water resources exhibit a distribution pattern of more in the north than south, more in the west than east, and more in mountainous areas than plains. Regionally, Bayingolin, with the largest administrative area, has the greatest total precipitation water resources at 616.5$×10^{8}$ m^{3}, followed by Hotan, Altay, and Tacheng Prefectures (250–320$×10^{8}$ m^{3}), while Shihezi City has the smallest amount. Xinjiang' s unit-area annual precipitation water resources are 16.3$×10^{4}$ m$^{3} \cdot km^{-2}$, only 24.6% of the national average. Northern Xinjiang prefectures are relatively rich in precipitation water resources, while southern Xinjiang prefectures are relatively poor. Ili Prefecture is the most precipitation-abundant region in Xinjiang, with unit-area annual precipitation water resources of 32.3$×10^{4}$ m$^{3} \cdot km^{-2}$, though this still reaches only 51.6% of the national average.

3.3 Atmospheric Water Vapor Resources From 1961 to 2022, an average of 21115$×10^{8}$ m^{3} of water vapor annually entered Xinjiang, while 20767$×10^{8}$ m^{3} flowed out, resulting in a net water vapor income of 347.5$×10^{8}$ m^{3}. The western, southern, and northern boundaries were dominated by water vapor input (21848.8$×10^{8}$ m^{3}, 1940.3$×10^{8}$ m^{3}, and 2613.5$×10^{8}$ m^{3}, respectively), while the eastern boundary was dominated by water vapor output (20819.8$×10^{8}$ m^{3}).

In terms of trends, total water vapor input and output over Xinjiang showed weak decreasing trends with consistent rates, while net water vapor income showed a weak increasing trend. Seasonally, water vapor transport through Xinjiang was greatest in summer, with total input and output accounting for 35.7% and 36.9% of annual transport, respectively. Spring and autumn were comparable, each accounting for approximately 23–25% of annual transport, while winter had the smallest transport at 13.3%. Net water vapor income was dominated by spring and winter (331.4$×10^{8}$ m^{3} and 144.6$×10^{8}$ m^{3}, respectively).

From a boundary perspective, the western boundary received water vapor input in all seasons (24.0%, 37.7%, 25.0%, and 17.1% of annual input for spring, summer, autumn, and winter, respectively). The southern boundary received northward water vapor input in all seasons (25.5%, 36.8%, 19.4%, and 13.7%, respectively). The eastern boundary showed water vapor output in all seasons (37.4%, 33.3%, 12.2%, and 36.9%, respectively), while the northern boundary showed southward water vapor output (23.2%, 14.5%, 23.2%, and 14.5%, respectively).

From 1961 to 2022, water vapor input and output in Xinjiang showed weak decreasing trends at rates of -69.6$×10^{8}$ m$^{3} \cdot (10a)^{-1}$ and -36.4$×10^{8}$ m$^{3} \cdot (10a)^{-1}$, respectively ($p > 0.05$). The decreasing trend in water vapor output was more pronounced than that of input, leading to an increasing trend in net water vapor income at a rate of 33.2$×10^{8}$ m$^{3} \cdot (10a)^{-1}$ ($p > 0.05$). Analysis of zonal and meridional water vapor transport revealed no significant trend in zonal transport, while meridional transport increased at a rate of 32×10^{8} $\text{m}^3\cdot(10\text{a})^{-1}$. This occurs because water vapor primarily originates from net zonal water vapor flux (i.e., net westerly water vapor flux), which remained in surplus throughout the study period. Variations in westerly intensity dominated water vapor input changes, with weakening mid-latitude westerlies reducing overall water vapor input to Xinjiang. However, the decreasing trend in water vapor outflow through the eastern boundary was more substantial, primarily due to enhanced anticyclonic anomalies over Lake Baikal east of Xinjiang, which inhibited water vapor outflow. Simultaneously, enhanced cyclonic anomalies over Central Asia west of Xinjiang strengthened meridional circulation, allowing more southwest-path water vapor to enter Xinjiang. These combined effects increased atmospheric water vapor content and net water vapor income over Xinjiang.

Xinjiang’ s water vapor transport exhibited distinct phased changes. Net water vapor income showed three phases: a weak increase from 1961–1987 (270×10^{8} $\text{m}^3\cdot(10\text{a})^{-1}$, $p > 0.05$), a significant decrease from 1988–2002 (-1325×10^{8} $\text{m}^3\cdot(10\text{a})^{-1}$, $p < 0.05$), and a fluctuating increase from 2003–2022 (392×10^{8} $\text{m}^3\cdot(10\text{a})^{-1}$, $p > 0.05$). Zonal and meridional water vapor transport also showed three phases with differing trends. Zonal transport experienced decreasing-increasing-decreasing changes, while meridional transport showed increasing-decreasing-increasing changes. Although net water vapor income trends aligned with meridional transport changes, climatologically, Xinjiang’ s water vapor inflow remained dominated by zonal transport, with meridional transport more reflected in anomalous precipitation processes.

3.4 Precipitation Conversion Efficiency Precipitation conversion efficiency is the ratio of total precipitation to total atmospheric water vapor over a certain area and period, also called water vapor precipitation efficiency. From 1961 to 2022, Xinjiang’ s average precipitation conversion efficiency was relatively low at 12.5%. The trend shows a significant increase at a rate of $0.64\%\cdot(10\text{a})^{-1}$ ($p < 0.05$), indicating that under the background of climatic “warming and humidification,” Xinjiang’ s precipitation conversion efficiency increased by 13.6% from 11.1% to 13.6%.

3.5 Surface Water Resources and Changes According to Xinjiang Water Resources Bulletin data, Xinjiang’ s multi-year average water resources from 2001–2021 totaled 912.3×10^{8} m^3, with surface water resources of 864.1×10^{8} m^3. Both total and surface water resources showed interannual fluctuations following precipitation resource changes. Compared with 2001, water resources in 2020 increased by 75.6×10^{8} m^3 (9.56% increase), and surface water resources increased by 79.6×10^{8} m^3 (9.59% increase). Overall, Xinjiang’ s water resources were in a relatively abundant period from 2001–2021.

The water yield coefficient reflects a region’ s capacity to convert precipitation into water resources, calculated as the ratio of total water resources to precipitation resources. From 2001-2021, Xinjiang’ s average water yield coefficient was 0.32, with small variation (0.28-0.38), below the national average of 0.45. The coefficient showed a weak fluctuating decreasing trend at -0.012%·(10a)$^{-1}$. Notably, the water yield coefficient was significantly negatively correlated with precipitation resources ($r = -0.68$, $p < 0.05$). In 2016, when Xinjiang experienced its highest historical precipitation resources, the water yield coefficient was only 0.28.

4. Discussion

The uneven distribution of precipitation observation stations in Xinjiang, particularly the scarcity of mountain observations, affects scientific understanding of regional precipitation patterns. Different gridding interpolation schemes yield varying precipitation resource estimates for Xinjiang. For instance, the inverse distance weighting method and multiple regression method produced annual precipitation resources of 3086$×10^{8}$ m^{3} and 3098$×10^{8}$ m^{3}, respectively, while the gradient distance-square method yielded 2724$×10^{8}$ m^{3}. This study’ s estimate of 2717.12$×10^{8}$ m^{3} is similar to the latter, and the gradient distance-square method is considered optimal for Xinjiang precipitation interpolation. With increasing high-resolution observations from dense automatic weather stations, satellite remote sensing, and radar, future research should focus on refined precipitation resource studies under complex terrain influences to obtain more accurate data.

Xinjiang possesses abundant atmospheric water resources. This study estimates that approximately 21115$×10^{8}$ m^{3} of water vapor annually enters Xinjiang based on ERA-5 data, while NCEP/NCAR data indicate about 26114$×10^{8}$ m^{3}. Different data sources, spatial resolutions, time periods, and calculation boundaries yield different atmospheric water vapor totals. Additionally, spatial differences exist in total atmospheric water vapor, with the Tianshan, Altai, and Kunlun Mountains—major mountain systems along the path of westerly circulation—serving as windward slopes for precipitation weather systems. These areas facilitate water vapor convergence and orographic lifting, making them the most water vapor-rich regions. Meanwhile, under the background of northwestern climate “warming and humidification,” regional internal water cycling has intensified, with significant increases in atmospheric water vapor over mountains and surrounding oases, providing new opportunities for cloud water resource development and utilization. Therefore, fully leveraging the favorable conditions of climatic “warming and humidification” to improve cloud water resource conversion efficiency and increase precipitation resources represents a key scientific approach to addressing Xinjiang’ s water shortage.

This study focused on water vapor budgets and atmospheric water vapor resources, without investigating refined cloud water resource characteristics. It is important to note that atmospheric water vapor cannot directly form precipitation—only a small portion converts to cloud water, which then condenses to form precipitation. Improving the efficiency of cloud water condensation and precipitation formation is the foundation of cloud water resource development. Continuous monitoring of cloud precipitation physics is scarce in Xinjiang, limiting precise understanding of cloud water content, cloud water budgets, refined cloud water resource characteristics, and in-depth knowledge of cloud precipitation physical processes and efficiency. Since the 1980s, Xinjiang' s climate has been in a "warming and humidification" stage with increased precipitation and abundant river runoff. Although surface water and total water resources have increased by over 9% since 2001, interannual precipitation variability has increased, intensifying uncertainties in precipitation and surface water resources. Climate projections indicate that Xinjiang will continue warming and humidifying, but the warming rate will far exceed the humidification rate, increasing drought risks. Continuous temperature rise has accelerated glacier retreat and snowmelt, with the cryosphere in a state of persistent shrinkage. Long-term monitoring shows that the Urumqi River Source Glacier No. 1 in the Chinese Tianshan Mountains and the Muyis Island Glacier in the Altai Mountains are accelerating melt and experiencing high mass loss, with Glacier No. 1' s mass balance in 2020 reaching the second-lowest value on record and its terminus retreating the maximum observed distance. Climate models project that around the mid-21st century, small and medium-sized glaciers will reach a tipping point of irreversible change, with some eventually disappearing substantially or completely, causing sharp declines in solid water resources and glacial meltwater supply. The regulating function of the "solid reservoir" on runoff will weaken or disappear, reducing surface runoff stability. Under warming conditions, extreme climate and hydrological events occur more frequently, intensifying water cycle system instability and posing severe challenges to Xinjiang' s water resource security, with future water shortages becoming more prominent.

Addressing these research gaps, future studies should focus on: (1) Cloud precipitation physics and refined cloud water resources in arid regions, including comprehensive scientific experiments on ground and airborne cloud precipitation physics and cloud water resource monitoring, development, and utilization; research on cloud microphysical characteristics; and development of refined assessment methods for cloud water resources based on integrated observations. (2) Multi-phase water conversion relationships in arid regions, including studies on the "water vapor-precipitation-surface runoff" conversion process and revealing the mechanisms of accelerated multi-phase water conversion and causes of varying precipitation efficiencies under global change. (3) Precipitation efficiency and precipitation enhancement effects of typical cloud systems in arid regions, including spatiotemporal distribution patterns of precipitation efficiency in typical cloud systems, evaluation of precipitation amounts, development of monitoring and assessment technologies, and effect verification and comprehensive benefit evaluation methods for ecological restoration and glacier replenishment. (4) Airborne cloud water resource development and joint air-ground water resource regulation technology, including development of theoretical methods for optimizing atmospheric precipitation efficiency regulation and key technologies for joint regulation of airborne cloud water resources and surface water conservancy projects to achieve coupled utilization.

5. Conclusions

From 1961 to 2022, annual precipitation in Xinjiang showed an increasing trend at a rate of 8.5 mm·(10a)$^{-1}$, with the Tianshan Mountains showing the highest humidification rate, followed by northern Xinjiang, and southern Xinjiang the lowest. A significant increase occurred around 1987, with a multi-year average annual precipitation of 198.3 mm (22.7% increase). Xinjiang' s multi-year average annual precipitation water resources were 2717.12$×10ˆ{8}$ m^3, with unit-area precipitation water resources of 16.3$×10ˆ{4}$ m^3·km^{-2}. Per capita precipitation water resources were relatively high at 10.5$×10ˆ{3}$ m^3, though significant regional disparities existed.

From 1961 to 2022, an annual average of 21115$×10ˆ{8}$ m^3 of water vapor entered Xinjiang, with 20767$×10ˆ{8}$ m^3 flowing out, resulting in a net water vapor income of 347.5$×10ˆ{8}$ m^3. Total water vapor input and output showed weak decreasing trends, while net water vapor income showed a weak increasing trend. Net water vapor income exhibited three phases: weak increase (1961-1987), significant decrease (1988-2002), and fluctuating increase (2003-2022). Xinjiang's regional average precipitation conversion efficiency was 12.5%, showing a significant increasing trend at 0.64%·(10a)$^{-1}$.

From 2001 to 2021, Xinjiang' s average total water resources were 912.3$×10ˆ{8}$ m^3, with surface water resources of 864.1$×10ˆ{8}$ m^3. Compared with 2001, water resources in 2020 increased by 9.56%, indicating an overall abundant water period. Xinjiang' s average water yield coefficient was 0.32, showing a weak fluctuating decreasing trend that was significantly negatively correlated with precipitation resources.

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

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