Postprint: Advances in Research on Changes in Key Hydrological Elements and the Water Cycle in the Tianshan Region, Central Asia

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Abstract

The Tianshan Mountains are situated in the hinterland of the Eurasian continent and constitute a critical water source for the middle section of the Silk Road Economic Belt. The water cycle system in the Tianshan region is characterized by pronounced spatiotemporal heterogeneity, complex water source mechanisms, diverse runoff composition, and high vulnerability. Various components of the water cycle are significantly influenced by land surface patterns and climate change, with hydrological elements exhibiting highly sensitive responses to climate change, rendering existing watershed water cycle models inadequate for elucidating its internal mechanisms. Based on comprehensive literature review and research, this study systematically analyzed changes in key hydrological elements in the Tianshan region in the context of climate change, investigated water vapor sources, transport mechanisms, and changes in water cycle elements under the weak water vapor sink effect along with their impacts on and contribution rates to precipitation in the Tianshan region, revealed the impact mechanisms of climate change on runoff generation and confluence processes and water resource variations in the Tianshan region, analyzed the effects of climate change on precipitation, glacier accumulation and ablation, and snow cover changes on the water cycle, proposed key research topics for water cycle studies in the Tianshan region, and provided a scientific basis for understanding water cycle mechanisms in arid mountainous regions and ensuring water resource security for the middle section of the national Silk Road Economic Belt.

Full Text

Changes of Key Hydrological Elements and Research Progress of Water Cycle in the Tianshan Mountains, Central Asia

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Abstract

Located in the hinterland of Eurasia, the Tianshan Mountains constitute a critical water source for the middle segment of the Silk Road Economic Belt. The water cycle system in this region is characterized by pronounced spatiotemporal heterogeneity, complex water generation mechanisms, diverse runoff composition, and high system vulnerability. Each component of the water cycle is significantly influenced by land surface patterns and climate change, with hydrological elements exhibiting sensitive responses to climatic fluctuations. Consequently, existing watershed water cycle models are inadequate for elucidating the underlying mechanisms. Through comprehensive literature review and research, this paper systematically analyzes changes in key hydrological elements under climate change, investigates water vapor sources and transport mechanisms in the Tianshan Mountains, examines variations in water cycle elements under weak moisture sink conditions and their impacts on regional precipitation, reveals the influence mechanisms of climate change on runoff generation processes and water resource dynamics, and analyzes the effects of climate-induced melting and snow cover changes on the water cycle. The paper concludes by identifying critical research priorities for understanding the water cycle in the Tianshan region, providing a scientific foundation for comprehending hydrological mechanisms in arid mountainous areas and ensuring water resource security along the Silk Road Economic Belt.

Keywords: hydrological elements; water cycle; hydrology and water resources; climate change; Tianshan Mountains in Central Asia

1. Research Background

The Tianshan Mountains, situated in the heart of the Eurasian continent, serve as a vital water source for the middle segment of the Silk Road Economic Belt, nurturing numerous rivers with annual runoff exceeding 100×10^8 m^3 in the arid regions of Central Asia. The water cycle processes in the Tianshan region are distinctive, with low system stability. Systematic investigation of the water cycle and water security in this region holds significant practical importance for building a community with a shared future in Central Asia and advancing Belt and Road cooperation.

1.1 The "Central Asian Water Tower" : Primary Water Source for Arid Central Asia

Known as the "Central Asian Water Tower," the Tianshan Mountains feature extensive glaciers and widespread snow cover. Water resources primarily consist of meltwater from high-altitude glaciers and snow, precipitation in mid-altitude forest zones, and bedrock fissure water in low mountain areas. According to the latest IPCC report, global mean surface temperature has increased by 0.95–1.09°C relative to pre-industrial levels, with land surface warming exceeding oceanic warming. The Tianshan Mountains have experienced particularly pronounced warming at rates of 0.30–0.41°C per decade, which has accelerated glacier retreat, snow melt, and permafrost degradation. These changes will inevitably affect water resource quantity and system stability in the Tianshan region, with implications for social stability in Central Asia and the development of the Silk Road Economic Belt.

1.2 Unique Hydrological Cycle Unsuitable for Existing Models

The Tianshan Mountains exhibit dramatic topographic relief and significant spatial variations in thermal distribution. Coupled with diverse water sources (glacial melt, snowmelt, atmospheric precipitation) and complex runoff generation mechanisms, the region' s water cycle processes are unique. Hydrological processes demonstrate extreme sensitivity to climate change, with minor-scale variations potentially producing substantial spatiotemporal differences. Consequently, existing watershed water cycle models and hydrological frameworks cannot adequately explain the underlying mechanisms and fundamental patterns. Climate warming has disrupted the natural equilibrium by altering precipitation patterns and glacial melt regimes, changing the temporal distribution and form of precipitation (rain-snow ratio), modifying river runoff recharge mechanisms, runoff generation processes, and discharge volumes, and intensifying extreme hydrological events. Rivers in the Tianshan region are heavily dependent on glacial and snow melt. As glaciers retreat and their regulating function declines, coupled with intensifying extreme climatic and hydrological events, runoff variability increases, water source mechanisms and runoff generation processes will transform, and river hydrological regimes will become increasingly complex. The impacts of future climate change on water resources in the Tianshan region remain uncertain, making the water cycle and water resource change trends a focal point in climate change science and arid zone hydrology.

1.3 Political Fragmentation Hindering Integrated Research

As an independent mega-tectonic geomorphic unit, the Tianshan Mountains connect China' s Xinjiang region with three of the five Central Asian countries (Kazakhstan, Kyrgyzstan, and Uzbekistan). This unique geopolitical setting, where water resource formation and consumption zones overlap, combined with differing water development objectives and management approaches among riparian nations, complicates integrated water resource development and management. The Tianshan region is the source of numerous international rivers with complex, dense transboundary networks, representing one of the world' s most prominent transboundary river issue hotspots. The multi-national span fragments the systematic and integrated nature of scientific research, leaving many questions regarding water cycle mechanisms and system changes in the Tianshan region still under debate.

2. Research Progress on Key Hydrological Elements

2.1 Precipitation Changes

Precipitation represents the most active component of the water cycle and the most critical hydrological element in the Tianshan Mountains. Over recent decades, precipitation has exhibited an increasing trend at a rate of 5.82 mm per decade. However, since 2000, this increasing trend has weakened while extreme precipitation events have become more frequent. Notably, under global warming, solid precipitation in mountainous areas shows a transition trend toward liquid precipitation. Studies indicate that for every 1°C temperature increase, the snowfall ratio decreases by 10.0%–15.0%. In High Mountain Asia, future temperature increases, particularly substantial winter warming, will reduce snowfall rates by 9.0%-24.0% under RCP4.5 and RCP8.5 scenarios. Under high-emission scenarios, rainfall-dominated areas will expand while snowfall-dominated areas will contract. The Tianshan Mountains have also experienced a significant decline in snowfall ratio, decreasing at rates of 0.6% per decade before 1990 and 0.5% per decade thereafter, primarily in mid- to low-altitude regions.

2.2 Glacier Changes

Glaciers constitute a crucial component of water resources in the Tianshan region, with glacial meltwater accounting for 20.0%–40.0% of total runoff. During warm, dry years, this proportion can reach 40.0% due to reduced precipitation and increased melting. While individual glacier studies have been relatively comprehensive regarding volume, thickness, and dynamics, understanding of the entire Tianshan glacier system remains limited, particularly under future climate scenarios. Research indicates that between 1961 and 2012, Tianshan glacier area and mass decreased by 18.0% ± 6.0% and 27.0% ± 15.0%, respectively, with accelerated retreat rates. In the Aksu River basin of central Tianshan, glacier mass balance reached -0.35 ± 0.34 m w.e. a^{-1}, while the North and South Inylchek glaciers experienced mass loss rates of -0.25 ± 0.10 and -0.43 ± 0.10 m w.e. a^{-1}, respectively. Chinese studies show that 10.3%-27.7% of glacier area has retreated over the past 50 years, with the most rapid retreat in central Tianshan and slowest in eastern Tianshan.

Future projections suggest that under RCP8.5, temperature increases of 1.5°C and 2.1 ± 0.1°C by the end of the 21st century will reduce glacier area by 64.0% ± 5.0% and 49.0% ± 7.0%, respectively. Under RCP4.5 and RCP6.0 scenarios, glacier losses will reach 54.4%-65.1% and 59.4%, respectively. To maintain current glacier mass balance under 1.5°C warming, precipitation at the same elevation would need to increase by 100 mm. By the end of the century, the glacier equilibrium line will rise by 570 m, reducing glacier area to 17.9% of the region.

2.3 Snow Cover Changes

Snow cover represents important solid water storage in the Tianshan Mountains. Recent studies show that between 2001 and 2015, snow cover decreased in 53% of the region and increased in 47%, with maximum and minimum snow cover decline rates of 0.62% a^{-1} and 0.04% a^{-1}, respectively. Spatially, snow cover decreases from high to low altitudes and from northwest to southeast. Snow-covered days exhibit heterogeneity, decreasing in central and eastern Tianshan while increasing in northern and western Tianshan. Notably, snow onset dates are advancing at -0.25 $d \cdot a^{-1}$, while snow duration shows a non-significant increasing trend (0.31 $d \cdot a^{-1}$), likely related to autumn temperature declines associated with North Pacific sea surface temperatures and strengthened Siberian High pressure. Snow depth has also increased in the Tianshan Mountains.

3. Mechanism Studies

3.1 Water Vapor Transport Mechanisms

Situated in the arid interior of the Eurasian continent, the Tianshan Mountains are influenced by overlapping Indian Ocean warm-moist airflow and Atlantic air masses, as well as westerly circulation. Atmospheric moisture originates primarily from the Arctic Ocean, Atlantic Ocean, and Caspian Sea, with recycled moisture from within the Eurasian continent contributing significantly to local precipitation. Studies using NCEP/NCAR reanalysis data and Lagrangian backward trajectory models indicate that Tianshan precipitation moisture mainly comes from terrestrial local water recycling rather than Atlantic Ocean moisture. In cold years, moisture originates more from high-latitude Arctic sources compared to warm years. High moisture values occur in valley plains on the northern Tianshan slopes, while low values appear in central and eastern Tianshan, decreasing exponentially with altitude. The evaporation-to-precipitation ratio is 94.39%, with maximum sub-cloud evaporation in summer. Atmospheric warming and moistening enhance local water recycling, with precipitation recycling rates averaging 6.48%-7.79% according to Brubaker and Schär models. Precipitation recycling showed strong upward trends in the early 21st century, indicating accelerated precipitation cycling in the Tianshan region.

3.2 Water Cycle Changes

As the "Central Asian Water Tower," the Tianshan water cycle process has attracted considerable attention. In Central Asian arid regions, nearly all rivers originate in mountains, yet mountain runoff systems are non-linear in their response to water cycle element changes (evaporation, snow cover, glaciers, etc.). Climate change inevitably alters the water cycle, affecting river recharge characteristics, seasonal runoff distribution, and discharge volumes, posing challenges to already strained water resource supply-demand balances. While precipitation changes primarily affect runoff magnitude and seasonal allocation, the impact of precipitation form changes on runoff remains uncertain. Barnett et al. suggest that reduced snowfall ratios in snowmelt-dominated regions may shift rivers from snowmelt-dominated to rainfall-dominated regimes, moving runoff peaks to winter and early spring rather than summer-autumn when water demand is highest.

Accelerating glacial melt under global warming has altered hydrological processes in glacier-fed rivers. Since peak flow timing depends on snowmelt dates and snow-covered area, rivers with substantial snowmelt components in the Tianshan region have experienced seasonal shifts in maximum discharge, manifested as earlier snowmelt flood peaks. Climate warming has also affected runoff composition, with some northern Tianshan catchments shifting from single-peak to double-peak runoff patterns. Global warming has disrupted natural equilibrium, accelerating melt of glaciers, snow, and permafrost, directly impacting regional water resource redistribution patterns and influencing water management strategy development.

3.3 Future Hydrological and Water Resource Projections

Data scarcity and unique hydrological processes in the Tianshan Mountains, combined with complex runoff generation mechanisms, make accurate water cycle simulation crucial for projecting water resource trends. Coupled climate-land surface-hydrological models have become the primary tool for analyzing future regional hydrological evolution. However, global climate model grid data produce large errors for the topographically complex Tianshan region, failing to capture dramatic climate factor variations in runoff-producing areas. Therefore, developing high-resolution regional climate models that represent arid mountainous land surface patterns is essential for studying future climate-hydrology trends. Some studies project continued runoff increases in High Mountain Asia before 2050, while others examine typical Tianshan catchments (Aksu, Kaidu, Amu Darya tributaries, Manas). However, data scarcity, particularly meteorological and hydrological observations under complex terrain conditions, creates substantial uncertainty in hydrological and water resource projections, with few high-precision watershed-scale integrated simulation studies.

4. Critical Research Priorities

4.1 Identifying Water Vapor Sources and Their Contribution to Mountain Precipitation

Influenced by the convergence of westerly circulation, Indian Ocean warm-moist airflow, and Atlantic air masses, the Tianshan region exhibits substantial precipitation variations across different regions, altitudes, slopes, seasons, and years due to unique basin-mountain terrain and complex climate patterns. Under global change, priority should be given to studying atmospheric water cycle structural evolution and its impact mechanisms on precipitation, clarifying contributions of different moisture sources (westerlies, Indian Ocean airflow, local evaporation) and pathways to regional precipitation. Research should analyze moisture source-sink distributions and transport channel characteristics for regional precipitation, extreme rainfall, and snowstorms, and reveal water cycle dynamic convergence mechanisms under large-scale atmospheric circulation and complex local topography.

4.2 Developing Physically-Based Distributed Hydrological Models for Complex Alpine Terrain

Sparse climate-hydrology stations and complex alpine topography in the Tianshan region have resulted in limited understanding of key hydrological processes (precipitation, evapotranspiration, surface runoff, baseflow) and their interactions. Systematic analysis is needed to understand hydrological processes and water source mechanisms under climate change, identify water resource composition and variation patterns, and interpret impacts of global change on runoff generation, peak flows, and baseflow changes. Constructing distributed hydrological models suitable for complex alpine terrain and data-scarce conditions is critical. These models must reflect the unique water source composition of the Tianshan region (rainfall, glacial melt, snowmelt). Multi-objective sensitivity analysis and optimization, combined with multi-source validation using glacial area/volume, snow cover, and isotopic data from different water sources, will improve scientific understanding of water cycle mechanisms in this unique region.

4.3 Elucidating Land-Atmosphere Energy-Water Exchange Mechanisms

The sensitive response of the Tianshan region to global change has made climate change-runoff relationships a research hotspot. While relevant results exist, in-depth analysis of runoff components, hydrological variables, peak flows, and low-flow periods remains limited. The non-linear nature of glacial area/thickness changes and complex snow hydrological processes have increased uncertainty regarding impacts of glacial-snow changes and extreme climatic-hydrological events on the water cycle. Global warming-induced changes in the hydrothermal pattern have introduced greater uncertainty to the already sensitive water cycle processes. Systematic research is needed on water cycle element trends and climate responses, analyzing impacts on precipitation (form and amount), melting, and snow area/thickness changes. This requires parsing spatiotemporal differences in water cycle changes and their root causes, and revealing land-atmosphere energy-water exchange mechanisms to accurately characterize the unique water cycle and runoff drivers in the Tianshan region.

4.4 Understanding Rain-Snow-Ice Changes and Runoff Generation for Future Projections

Temperature increases in the Tianshan region affect not only precipitation amount and form but also melting rates and runoff recharge mechanisms. While relationships between glacial/snow area and climate change have been studied, analysis of ice-snow-permafrost changes relative to water storage, including rates, trends, and mechanisms, remains scarce. The mechanisms by which rain-snow-ice changes affect runoff processes are still unclear. Under global climate change, with increasing uncertainty in glacial-snow dynamics and changing precipitation patterns, systematic research is needed on mountain precipitation, ice-snow distribution and changes, and rain-snow-ice runoff processes. This is crucial for projecting future water cycle processes and water resource trends under different scenarios, providing essential scientific support for water security in the Silk Road Economic Belt.

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