

Long-Term Glaciological Observations Guiding Research on Glacier Changes and Impacts in Continental and Arid Regions: Postprint

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Date: 2023-03-19T00:00:00+00:00

Abstract

China is a major country of mid-latitude mountain glaciers, and scientific research on glaciers is of paramount importance. Glaciers also constitute crucial water resources in the arid regions of western China—the source of major rivers for China and neighboring countries. Hydrological and water resource changes induced by glacier variations are of decisive significance to the ecosystems of the mountain-basin physiographic structure in northwestern China’s arid regions. The Tianshan Glacier Observation and Test Station of the Chinese Academy of Sciences (hereinafter referred to as “Tianshan Glacier Station”), established in 1959 at the dawn of Chinese glaciology, has played a pivotal role in the formation and development of glacier science theory in China through research centered on the Urumqi River Headwater Glacier No. 1 (hereinafter referred to as “Glacier No. 1”), and constitutes an important development and contribution to international glaciology. Hydrological studies based on comprehensive observation and testing in the Urumqi River mountainous watershed have established the foundation for hydrological research in China’s inland river basins. Over the past 60 years, as a base for observation, testing, research, and talent training in Chinese glaciology and a platform for open exchange with the outside world, Tianshan Glacier Station has achieved systematic innovative results in research directions such as glacier physics, glacier response to climate change, glacier hydrology, snow and ice physicochemical processes, Quaternary glaciers, and periglacial vegetation and ecology, making outstanding contributions to the cause of glaciology in China. The World Glacier Monitoring Service (WGMS) has listed Glacier No. 1 as one of ten reference glaciers for key observation and research worldwide, namely as a reference glacier for China and the arid regions of Central Asia, with its long-term, systematic observation and research becoming a reference and model for glacier studies in many nations.

Full Text

Introduction

China is a major mid-latitude mountainous glacier country, with glaciers covering more than 10% of the Earth's surface area. Glaciers represent a crucial solid water reservoir, storing 68.7% of the world's freshwater resources. Globally (excluding Antarctic and Greenland ice sheets), there are 215,547 mountain glaciers with a total area of 705,739 km², with an average individual glacier area of 3.28 km², predominantly high-altitude continental glaciers. In China and neighboring countries, glaciers serve as the headwaters of major rivers, and hydrological changes triggered by glacier variation have decisive significance for the ecosystem of the mountain-basin geographical structure in China's arid northwestern regions.

The Tianshan Glaciological Station (hereinafter referred to as "TGS") of the Chinese Academy of Sciences (CAS) was established in 1959 at the dawn of Chinese glaciology. Research centered on Urumqi Glacier No. 1 (hereinafter referred to as "Glacier No. 1") in the Urumqi River headwaters has played a pivotal role in the formation and development of Chinese glacier science theory, representing an important contribution and advancement to international glaciology. Hydrological research based on comprehensive observation experiments in the Urumqi River mountainous watershed laid the foundation for inland river hydrology studies in China. Over the past 60 years, TGS has served as a base for glacier observation, experimentation, research, and talent cultivation in China, as well as a platform for international exchange, achieving systematic innovative results in glacier physics, glacier response to climate change, glacier hydrology, snow-ice physical-chemical processes, Quaternary glaciation, and periglacial vegetation and ecology, making outstanding contributions to China's glaciology enterprise. The World Glacier Monitoring Service (WGMS) has designated Glacier No. 1 as one of ten globally key reference glaciers, serving as the reference glacier for China and Central Asian arid regions. Its long-term, systematic observation and research have become a reference and model for glacier studies in many countries [1-4].

Glacier Coverage and Significance

China possesses 48,571 glaciers covering a total area of 5.18×10^4 km², accounting for 11–14.5% of the global mountain glacier area. These glaciers constitute the vital "Asian Water Tower," sustaining ecological environments and ensuring water supply for urban, industrial, agricultural, and domestic use in western China's arid regions. Glacier meltwater contributes 25–29% to mountain runoff, playing a pivotal role in water resources while functioning as a "solid reservoir" that regulates river discharge across interannual and intra-annual timescales. Climate warming first increases glacier meltwater runoff at the cost of consuming solid ice reserves. As glacier storage rapidly diminishes, meltwater runoff will subsequently decline sharply. Intense glacier melting also

triggers glacier hazards including floods and debris flows.

In China's western arid region, there are 20,695 glaciers in Xinjiang, 3,802 in Qinghai, and 1,538 in Gansu, with a combined area of 27,360.73 km². Over the past 30 years, global glaciers have accelerated their retreat, causing sea-level rise, altered water cycles, and increased glacier-related hazards. The IPCC Fifth Assessment Report indicates that since the Last Glacial Maximum, global sea level has risen by 120 m, primarily due to ice sheet and glacier melt. Mountain glaciers currently contribute (0.76 \pm 0.37) mm/a to sea-level rise, making them the second-largest contributor after ocean thermal expansion.

The Tianshan Glaciological Station: History and Network Development

Establishing glacier observation networks is extremely challenging due to extreme cold, thin air, sparse population, and poor accessibility. Fewer than five glaciers worldwide have observation records exceeding 50 years, and only about 40 have records over 30 years. Glaciological data are globally scarce, making glaciology a discipline developed based on observations from a limited number of glaciers.

TGS was established in 1959, marking China's transition from sporadic field surveys to systematic positioning observations. Research on Glacier No. 1 filled numerous gaps in international glaciology, which had been based primarily on maritime glaciers and ice sheets, lacking observations of continental and arid-region glaciers. To better study glaciers across northwestern China's arid regions, TGS has continuously expanded its monitoring network beyond Glacier No. 1:

- In August 1998, the Hashilegen Glacier No. 51 in the Kuitun River basin was selected as the second reference glacier, with 20 years of observation data accumulated to date.
- In August 2004 and August 2008, the Miaoergou Ice Cap in Hami and the Qingbintan Glacier No. 72 on Mt. Tomur were selected as the third and fourth reference glaciers, respectively.
- In 2011, TGS signed an agreement with the Kanas Scenic Area Administration to establish the "Altay Mountains Glacier, Snow and Environment Observation Research Station," and in 2016, jointly established the "Altay Cryosphere Science and Sustainable Development Comprehensive Observation Research Station" with Jeminay County government, designating the Muxide Glacier as a reference glacier.
- In October 2010, TGS expanded its observations to the Qilian Mountains, naming the largest glacier in the Hulugou watershed of the upper Heihe River basin as "Glacier No. 11" and conducting continuous systematic observations in collaboration with the Heihe Upstream Eco-Hydrological Experimental Research Station.

Additionally, TGS established semi-permanent observation points for glaciers

including the Sectors Glacier on Bogda Peak, Glacier No. 4 in the Sigong River basin, the Lujiaowan Glacier in the Manas River headwaters, Glacier No. 48 in the Kuitun River basin, Glacier No. 18 in the Burqin River basin of the Altay Mountains, and the Kelayiylake Glacier on Mt. Kongur. These permanent and semi-permanent stations form a comprehensive monitoring network covering glaciers across northwestern China's arid regions. In 2014, TGS assumed responsibility for observing two reference glaciers at China's Arctic Yellow River Station (Austre Lovénbreen and Pedersenbreen), applying TGS observation protocols to polar regions.

Standardization and International Integration

TGS strengthened and standardized observation methods and data quality control to achieve full international integration. The station developed *Glacier and Related Observation Methods and Specifications* [5] and *Basic Principles of Glacier Dynamics Models and Parameter Observation Guidelines* [6], which have become widely applied observation manuals in other glacier research regions. In 2010, WGMS convened an international meeting in Switzerland to formulate a 10-year plan for global glacier monitoring, where TGS's glacier monitoring plan and data specifications for Central Asian arid regions were adopted. In 2013, TGS joined the Global Cryosphere Watch (GCW) program created by the World Meteorological Organization (WMO).

TGS observation data are published domestically through multiple platforms including the *Tianshan Glaciological Station Annual Report*, Cold and Arid Regions Science Data Center, and Cryosphere Science Data Platform. International data release follows WGMS and GCW requirements, regularly published in datasets including *Glacier Mass Balance Bulletin* (with Glacier No. 1 featured on the cover of Issue 9, [Figure 1: see original paper]), *Fluctuations of Glaciers*, *Global Glacier Change Bulletin*, and the GCW website. These data are also included in the UNEP *Environmental Data Report* dataset, Geo Data Portal, and China's *Climate Change Blue Book*. The IPCC Third, Fourth, and Fifth Assessment Reports, along with at least eight articles published in *Nature* and *Science*, have utilized these observation data.

Glacier Physics and Mass Balance Research

In the early 1980s, TGS pioneered glacier physics research in China. Through long-term mass balance observations, the station discovered that mountain glaciers have undergone two acceleration periods of melting, revealing four major mechanisms of accelerated glacier retreat [10-14]. Based on Glacier No. 1 research, these mechanisms are: (1) rising temperatures during the ablation season directly increase melt; (2) increased glacier ice temperature reduces energy required to reach melting point and increases refreezing, enhancing glacier sensitivity to warming; (3) expanding ablation area lowers surface albedo through increased cryoconite and mineral dust, creating a positive feedback mechanism;

and (4) glacier fragmentation increases effective melt area and facilitates meltwater penetration, intensifying ablation.

Glacier mass balance is a crucial glaciological parameter representing accumulation and ablation. WGMS identified that Glacier No. 1's mass balance curve closely resembles the global average in both magnitude and pattern [Figure 2: see original paper], making it representative of global mountain glacier trends. In 2007, WGMS selected 30 reference glaciers to establish a global mass balance standard curve, with Glacier No. 1 included as China's and Central Asia's representative.

TGS monitoring shows that from 1960–2017, Glacier No. 1 had an average mass balance of -341 mm/a, with accelerating retreat. Two acceleration periods occurred: the first around 1985, when the average mass balance shifted from -81 mm/a (1960–1984) to -273 mm/a (1985–1996); the second beginning in 1997 was more intense, with the 1997–2017 average reaching -690 mm/a. In 2010, the mass balance dropped to $-1,327$ mm, the lowest recorded value. Since 2011, mass balance has shown fluctuating changes, with a temporary slowdown in 2011–2014 followed by renewed high mass loss. The cumulative mass balance from 1960–2017 reached $-19,774$ mm water equivalent, indicating an average thickness reduction of $19,774$ mm under constant area conditions.

Hydrological Research in the Urumqi River Basin

In China's northwestern inland and Central Asian arid regions, water resources constrain socioeconomic development and sustain ecological environments. Mountains constitute water formation zones. Based on comprehensive observation experiments in the Urumqi River mountainous watershed, TGS revealed characteristics of glaciers, snow cover, alpine permafrost, and mountain precipitation-runoff. Using water balance principles and energy-water balance models, the station studied runoff formation and transformation between surface and groundwater, and coupled glacier models with hydrological models to simulate dynamic runoff responses to climate change. This research established the foundation for inland river hydrology and water resources studies in China.

TGS initiated observations of glacier surface energy balance, meltwater contributions to rivers, glacier basin hydrological characteristics, and surface-groundwater conversion during 1959–1965. After reconstruction in 1979, the station established a hydrometeorological gradient observation network in the Urumqi River basin, forming China's basic framework for hydrological and meteorological process observation in glacierized watersheds [15–21]. Since 1995, TGS expanded its research area, developed glacier hydrological models, and conducted simulation studies on glacier water resource changes across the entire arid region.

Accelerated glacier retreat since the 1980s has altered water resource spatiotemporal distribution and water cycle processes, profoundly impacting Xinjiang's development patterns. Recent observations and simulations indicate that glaciers

in the Mt. Tomur region are melting faster than expected. Unless temperatures rise substantially, meltwater will not continue increasing. Future meltwater runoff sensitivity to temperature changes will intensify. In the Tarim River basin, where glacier meltwater constitutes a large proportion, catastrophic water resource impacts will occur when most glaciers disappear.

Glacier change impacts vary significantly across different watersheds of the Tianshan region. For small-glacier rivers like the Urumqi River, meltwater will continuously decrease until disappearing, losing glacier supplementation and regulation. For large-glacier rivers like the Manas River, meltwater will maintain certain proportions. Glaciers in eastern Xinjiang basin water systems are in accelerated retreat, with water supply continuously deteriorating. In the Qilian Mountains' Heihe River basin, 90.7% of glaciers (by number) will disappear by 2040, with area loss exceeding 59.4%. The Shule River basin will likely see 429 glaciers disappear before 2040, with catastrophic impacts due to its high meltwater contribution (>30%). Over the past 50 years, glacier shrinkage in the Shiyang River basin has significantly reduced river discharge, and by around 2040, most glaciers will disappear, causing water resource and ecological changes requiring further study.

Glacier Modeling and Future Projections

The TGS glacier model, independently developed by TGS, enables simulation and prediction at both individual glacier and regional scales [23,24]. The model includes: (1) parameterization schemes for different glacier types and characteristics; (2) a mass balance model centered on simplified glacier surface energy/mass balance equations; (3) ice flow models suitable for mountain glaciers, including full-component, high-order, and shallow ice approximation models; (4) additional modules for boundary heat transfer and basal sliding; and (5) scaling models from reference glaciers to regional glaciers, including glacier bed morphology models.

Using this model, simulations for Glacier No. 1, Qingbintan Glacier No. 72, Miaoergou Ice Cap, and Qilian Mountains Glacier No. 11 were conducted under RCP4.5 emission scenarios [Figure 3: see original paper]. Results show that by the end of the 21st century, only Qingbintan Glacier No. 72 and Miaoergou Ice Cap (both >2 km²) will retain ice mass. Glacier volume, area, and length changes follow different processes, with length showing the greatest fluctuations. Under all emission scenarios, glaciers will rapidly retreat, with faster warming causing faster parameter changes but not altering the overall process. For small glaciers (<2 km²), different warming scenarios have minimal impact because initial warming rates are similar and glacier geometric changes primarily reflect integrated and lagged responses to past climate changes. Even without further climate change, glaciers will continue retreating until reaching equilibrium with climate conditions.

Sensitivity tests based on individual glacier simulations indicate that under

RCP4.5, 261 glaciers in the Chinese Altay Mountains (91.9% by number, 44.4% by area) will disappear before 2090, leaving 23 glaciers mainly in the Burqin River basin. In the Tianshan region, 5,870 glaciers (74.0% by number, 21.5% by area) will disappear faster than Glacier No. 1, with 2,147 remaining glaciers concentrated in the Tarim River basin (55.1%) and Manas River basin by 2090. In the Qilian Mountains, 1,838 glaciers (68.5% by number, 17.0% by area) will disappear faster than Glacier No. 11, with 846 remaining glaciers (87.6% concentrated in western Qilian Mountain watersheds (Shule, Haltang, and Tata rivers) by 2040, while eastern and central Qilian glaciers will essentially disappear.

Analysis reveals that glacier volume and its change process are primarily controlled by mass balance, which depends on regional climate and topographic conditions. Regional climate determines overall glacier scale, while topography determines individual glacier size. Glacier scale reflects the combined influence of mass balance and terrain, with glacier accumulation height being the most important topographic factor. Glacier area and length changes are characterized by alternating “retreat” and “thinning” patterns, with each transition creating an “inflection point” controlled by ice thickness distribution. For Chinese glaciers with summer accumulation, increased precipitation has limited protective effect on future changes. Statistical analysis shows significant linear relationships between glacier area and future ice volume changes for glaciers $<30 \text{ km}^2$. Under RCP4.5, all global glaciers $<2 \text{ km}^2$ will disappear by 2100, and glaciers $<10 \text{ km}^2$ will retain less than 30% of their current ice mass.

Snow-to-Ice Transformation Processes

To study the physical-chemical processes of snow transforming into glacier ice, TGS established an observation and sampling site in the 4,130 m accumulation zone of Glacier No. 1 in July 2002 [Figure 4: see original paper]. This project, known internationally as the PGPI (Glacier Process Project), attracted participation from research institutions in the US, Germany, and Japan, with over 60 academic papers published in mainstream glaciological journals and presented at the AGU Fall Meeting in December 2008.

Research shows that new snow evolves into glacier ice through physical processes while aerosols undergo chemical processes from atmospheric to snow layer to glacier records [25-30]. Compared to the 1960s, warming temperatures have shortened the time required for new snow to transform into fine-grained snow, coarse-grained snow, and glacier ice. Snow layer characteristics have changed significantly, with thinner layers, simpler structure, and blurred grain boundaries. Meltwater percolation has intensified, causing the ablation zone to expand continuously, the cold infiltration zone to disappear, and the boundaries between ice formation zones to shift upward. Even the glacier’s top edges show ablation zone characteristics under intense radiation.

During aerosol evolution from snow to glacier records, natural and anthro-

pogenic mineral dust, heavy metals, chemical ions, and oxygen isotope ratios are affected by elution processes with a critical daily mean temperature threshold of -3.6°C . Below this temperature, ablation's impact on records is negligible; above it, records require analytical correction. Climate warming intensifies elution, reducing ice core record resolution. These changes in snow-to-ice processes reduce ice core resolution while making glaciers more “warm-type” and increasing their sensitivity to climate change.

Achievements and Contributions

Over 60 years, TGS has achieved systematic original results in glaciology, Quaternary glaciation, glacier hydrology, and periglacial vegetation and ecology, addressing international glaciological trends and national demands for ice and snow water resources. The station has published over 20 monographs and more than 1,300 academic papers, including over 300 SCI papers (50+ in the mainstream journal *Journal of Glaciology*). TGS has trained numerous outstanding cryosphere science talents and received over 10 national and provincial awards, including one Second-Class National Natural Science Award, one Second-Class National Science and Technology Progress Award, two First-Class Provincial Natural Science Awards, five Second-Class Provincial Natural Science Awards, and two First-Class Provincial Science and Technology Progress Awards. The station has been honored twice as an Advanced Field Station by CAS.

The International Glaciological Society's (IGS) professional news journal *ICE* (Issue 157, 2011) noted: “Urumqi Glacier No. 1 is one of the few glaciers in the world with continuous 50-year mass balance observations. Research on Glacier No. 1 and its basin has contributed in a continuous stream to glacier physics and to meteorological, hydrological, and geomorphological research in glacierized areas, improving understanding of the ecological environment and glacier evolution in the Tianshan region. Today, TGS is an international cooperation platform and a model for observation and research based on field stations for China and other countries.”

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Abstract

China has 48,571 glaciers with a total area of 5.18×10^4 km², which accounts for 11–14.5% of the total area of mountain glaciers in the world. These glaciers constitute a vital source of water for more than 100 million people and for wildlife ecosystems in this vast arid and semi-arid land in northwestern China. Urumqi Glacier No. 1, the best monitored glacier in China, is located at the headwaters of the Urumqi River in eastern Tianshan and is within the core area of central Asia. To implement the long-term monitoring of Urumqi Glacier No. 1, the Tianshan Glaciological Station (TGS) was established by the Chinese Academy of Sciences (CAS) in 1959. Since then, Urumqi Glacier No. 1 has been the subject of extensive studies. Internationally, it has been one of the ten referential glaciers in the World Glacier Monitoring Service (WGMS), and considered to be of great importance because of its special geographical position. The Urumqi Glacier No. 1 complements similar long-term monitoring programs covering more maritime-type glaciers and glaciers in transitional climates in polar, temperate, and tropical regions. Over the past 60 years, TGS has served as a research and training base for domestic and overseas scientists and graduate students. It plays a central role in Central Asian climatological, hydrological, and glaciological research. As such, it is well known and highly regarded by the international scientific community. As a permanent year-round glacier station among glaciers in Central Asia, it is the benchmark to which other relevant studies can make reference.

Keywords: Urumqi Glacier No. 1, glacier mass balance, glacier hydrology, snow-glacier processes

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

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