Long-Term Research on Maritime Glaciers and Environmental Monitoring Supports Regional Sustainable Development: Postprint

Authors: Wang Shijin, Kang Shichang, Chen Tuo, He Yuanqing, Myricology, Li Quanlian, Niu Hewen, Pu Tao, Zhang Binglin, Che Yanjun, Guo Wanqin, Yan Xingguo, Ma Xinggang, Wang Rongjun

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Abstract

After 20 years of development, the Yulong Snow Mountain Cryosphere and Sustainable Development Field Scientific Observation and Research Station of the Chinese Academy of Sciences has established a comprehensive field observation system and online data visualization platform for maritime glaciers and the environment that integrates observation, research, demonstration, and service. Based on long-term fixed-point monitoring of maritime glaciers and their environment, this platform focuses on key scientific issues concerning sustainable development in maritime glacier regions, conducts in-depth analyses of the process mechanisms underlying maritime glacier changes, reveals the hydrological, microbial, and climatic effects of such changes, evaluates the effectiveness of maritime glacier tourism services and the comprehensive risk of glacial lake outburst disasters, with its research findings providing scientific and technological support for regional sustainable development.

Full Text

Preamble

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Authors: Wang Shijin[1,2,3], Kang Shichang[1,2], Chen Tuo[1,2], He Yuanqing[1,2], Yang Meixue[1,2], Li Quanlian[1,2], Niu Hewen[1,2], Pu Tao[1,2], Zhang Binglin[1,2,3], Che Yanjun[2,3], Guo Wanqin[1,2,3], Yan Xingguo[1,2,3], Ma Xinggang[1,2,3], Wang Rongjun[1,2,3]

[1] State Key Laboratory of Cryospheric Science and Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Yulong Snow Mountain National Field Observation and Research Station for Cryosphere and Sustainable Development, Chinese Academy of Sciences, Lijiang 674100, China
[3] Midui Glacier-Guangxie Lake Disaster Field Science Observation and Research Station of Tibet Autonomous Region, Chinese Academy of Sciences, Nyingchi 860000, China

Abstract

After nearly two decades of development, the Yulong Snow Mountain National Field Observation and Research Station for Cryosphere and Sustainable Development, Chinese Academy of Sciences, has established a comprehensive field observation system and online data visualization platform for temperate glaciers and their environment, integrating observation, research, demonstration, and service. Based on long-term positioning monitoring of temperate glaciers and their environment, and focusing on key scientific issues related to sustainable development in temperate glacier regions, this study deeply analyzes the process mechanisms of temperate glacier changes, reveals the hydrological, microbial, and climatic effects of these changes, evaluates the effectiveness of temperate glacier tourism services and the integrated risk of glacial lake outburst floods, providing scientific and technological support for regional sustainable development.

Keywords: long-term positioning monitoring, temperate glacier and environment, regional sustainable development, cryospheric science
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1. Establishment of a Comprehensive Observation Network for Temperate Glaciers and Environment in China

Global temperate glaciers (warm glaciers) are significantly influenced by oceanic climate and are highly sensitive to global warming. The Yulong Snow Mountain glaciers, located on the southeastern margin of the Qinghai-Tibetan Plateau, are also temperate glaciers due to the dual influence of South Asian and East Asian monsoons during summer and autumn. Temperate glaciers in China are relatively accessible and located near major tourism source markets such as Sichuan and Chongqing, making them significant for economic benefits. However, compared with continental glaciers (cold glaciers), temperate glaciers are characterized by higher ice temperatures and faster flow velocities under monsoon influence, resulting in more rapid retreat rates and attribute changes, with greater destabilization risks and potential impacts. Small temperature increases and precipitation fluctuations can cause dramatic glacier changes, making their study crucial for revealing global change indicators. To promote sustainable development in these regions, there is a strong practical need for positioned monitoring of the cryosphere and environment.

The Yulong Snow Mountain National Field Observation and Research Station for Cryosphere and Sustainable Development (hereinafter referred to as "Yulong Snow Mountain Station") is located in Baisha Town, Yulong County, Lijiang City, Yunnan Province. Established in 2006, it is China's first field station dedicated to monitoring and researching temperate glaciers and their environment. Yulong Snow Mountain, situated on the southeastern margin of the Qinghai-Tibetan Plateau, is the largest modern glacier distribution area nearest to the equator in Eurasia. Long-term positioned monitoring is crucial for revealing the process mechanisms of low-latitude, high-altitude glacier changes. Through years of development, Yulong Snow Mountain Station has made significant progress in field observation platform construction, research on temperate glacier change processes and mechanisms, environmental effects and impacts of temperate glacier changes, glacier tourism services, and collaborative research on glacial lake outburst disasters. These achievements have had important domestic and international influence, greatly promoting collaborative research between the cryosphere and sustainable development, and providing theoretical basis and decision-making support for optimizing regional water resource allocation, developing ice and snow tourism resources, and preventing cryospheric disasters.

Since its establishment, guided by cryospheric science objectives and major national social needs, Yulong Snow Mountain Station has adhered to the principle of "observation, research, demonstration, and service," gradually building a spatial observation network system of "One Station and Four Zones" (Yulong Snow Mountain Station, Meili Snow Mountain, Gangri Garbo, Gongga Snow Mountain, and Dagu Snow Mountain research areas) [Figure 1: see original paper], and strengthening collaborative observation and research capabilities for the cryosphere and sustainable development across the entire temperate glacier region. The Yulong Snow Mountain observation system includes five gradient meteorological monitoring systems at altitudes of 2,049–4,850 m, one glacier change positioning observation field, one real-time glacier monitoring system, one ice and snow chemical characteristics observation system, two glacier hydrological observation fields, and three atmospheric environment monitoring systems. The other four research zones are all equipped with meteorological and hydrological stations for positioned monitoring of glaciers, meteorology, and hydrology. The Gangri Garbo research area focuses on revealing glacier-glacial lake interaction mechanisms, the Meili Snow Mountain research area emphasizes clarifying the recharge effect of ice and snow runoff on groundwater, the Gongga Snow Mountain research area aims to reveal the inhibitory effect of debris cover on glacier mass loss, and the Dagu Snow Mountain glacier area focuses on the comprehensive impacts of snow and ice ablation processes on sustainable tourism. Based on this observation system, Yulong Snow Mountain Station has developed a cryosphere and sustainable development data visualization platform, enabling real-time online transmission of meteorological, glacier, and hydrological observation data from the "One Station and Four Zones."

Yulong Snow Mountain Station emphasizes quality control of observation methods and data, strengthens organic connection with national science and technology resource sharing service platforms, systematically carries out field observation data submission and sharing, and effectively promotes the openness of scientific facilities and data resources.

2. Conducted Positioning Monitoring and Comparative Studies of Mass Balance for Baishui River Glacier No.1 and Global Reference Glaciers

Based on long-term positioned monitoring, the longest time-series mass balance dataset for temperate glaciers nearest to the equator in Eurasia has been established [2], with collaborative comparison to global reference glacier mass balance, playing an important role in regional water resource utilization planning.

Since 2008, mass balance stakes have been deployed on Baishui River Glacier No.1 in Yulong Snow Mountain to conduct continuous mass balance monitoring. Using contour line methods, ablation curve methods, and geodetic methods, the average annual mass balance of Baishui River Glacier No.1 during 2000–2010 was calculated as –0.99, −1.01, and −1.18 m w.e., respectively, showing consistent results [3]. Between 1952 and 2017, the mass balance of Baishui River Glacier No.1 fluctuated significantly, ranging from –1.94 to 2.26 m w.e., with a cumulative mass balance of –27.45 m w.e., indicating severe mass loss over the past decades [Figure 2: see original paper]. This work revealed the rapid change mechanisms of temperate glaciers: weakened solid precipitation in glacier areas, increased ice melting, increased debris cover reducing snow and ice albedo, increased glacier surface fragmentation expanding ablation area, rapid ice temperature rise, and increased liquid precipitation in the firn basin during ablation periods [2]. Since the 1950s–1960s, the glacier area reduction rate in China's temperate glacier regions (Gangri Garbo, Dagu Snow Mountain, Yulong Snow Mountain, and Meili Snow Mountain) has exceeded 38%, far higher than the national average of 18% [1]. Between 1959 and 2015, mass balance changes in temperate glaciers were dramatic, with annual mass balance fluctuating between –1.80 and 0.44 m w.e., and an average annual mass balance decreasing rate of –0.037 m w.e./a. Baishui River Glacier No.1, Urumqi River Source Glacier No.1, and global reference glaciers all show similar mass loss trends. Over the past nearly 60 years, the average mass loss rates were 0.03, 0.02, and 0.01 m w.e./a, respectively. Baishui River Glacier No.1 shows a significantly faster ablation trend than Urumqi River Source Glacier No.1 and faster than the global reference glacier mass loss rate [1,2]. In 2022, Baishui River Glacier No.1 remained in a state of severe mass loss, with a mass balance reaching –1.65 m w.e.

3. Revealed Hydrological, Bacterial Microbial, and Climatic-Environmental Effects of Temperate Glacier Changes

(1) Contribution of Ice and Snow Melt to Surface Runoff and Groundwater

Using the Meili Snow Mountain Mingyong River basin, Yulong Snow Mountain Baishui River basin, and Yanggong River basin as study areas, and combining meteorological, hydrological, and isotopic data, an isotopic hydrograph separation model was established to quantitatively analyze the contribution of ice and snow meltwater to surface runoff in different basins. Results show that during the ablation period (June–September), ice and snow meltwater accounts for 58.4% of Mingyong River runoff, while groundwater accounts for the highest and most stable proportion (60.0%) during the non-ablation period. Pre-monsoon snowmelt contributes 38.3% to Baishui River basin surface runoff, while monsoon-period glacier melt contributes 61.1%. Pre-monsoon snowmelt contributes 47.9% to Yanggong River water, while monsoon-period glacier melt accounts for 6.8% of Yanggong River surface runoff [4]. Using a mass balance equation to separate Mingyong River groundwater into glacier melt and rainwater components, precipitation and glacier melt contributions to groundwater recharge in the Mingyong River basin were found to be 54%$±22±$22%, respectively, revealing a new phenomenon of non-monsoon precipitation dominating groundwater recharge in monsoon-affected temperate glacier areas [5].

(2) Differences in Bacterial Community Structure Between Glaciers and Their Retreat Areas and Influencing Factors

The low temperature, oligotrophic conditions, and strong radiation characteristics of glaciers make them a natural, unique microbial resource repository. Bacterial communities in different habitats (snow, ice, meltwater, soil, cryoconite, etc.) show significant differences. Bacterial community abundance in snow and ice is typically lower than in meltwater, soil, and cryoconite. Chinese glacier snow pits show an overall pattern of "higher in the north, lower in the south" in microbial quantity, diversity, and community composition, with continental glaciers having higher bacterial counts (culturable) than temperate glaciers. Bacterial counts in Baishui River Glacier No.1 snow pits increase with depth, but diversity and community structure show no significant changes, with dominant groups mainly Firmicutes and Actinobacteria [6]. Bacterial communities in Baishui River Glacier No.1 meltwater and retreat area soils both have high diversity but differ significantly in community composition. Meltwater is dominated by Proteobacteria, Firmicutes, and Cyanobacteria, while soils also have high abundances of Acidobacteria, Actinobacteria, and Bacteroidetes. Soil bacterial community diversity and structural similarity are higher than in meltwater, with these differences significantly correlated with different environmental physicochemical characteristics, where multiple indicators including total organic carbon (TOC), pH, and Fe have significant effects on bacterial communities. Collaborative comparison of global typical glacier retreat areas reveals that bacterial community structure is simultaneously influenced by climate and geographic patterns [7,8].

(3) Climate Effects of Glacier Light-Absorbing Impurities

Based on long-term observations, the spatial-temporal patterns, chemical transformation, enrichment-leaching processes, and mechanisms of light-absorbing impurity content in Baishui River Glacier No.1 were analyzed, revealing the climate effects of light-absorbing impurities and assessing the impact mechanism of black carbon (products of incomplete combustion of fossil fuels and biomass) on glacier ablation [Figure 3: see original paper]. In Baishui River Glacier No.1, as snow continues to melt, black carbon and organic carbon enrich on the ice surface, with black carbon enrichment being more significant. Under different light-absorbing impurity concentration scenarios, the degree of ice surface albedo reduction varies. Black carbon causes the highest degree of snow and ice albedo reduction, with black carbon and dust causing up to 15% albedo reduction in some temperate glaciers in southeastern Tibet. In Baishui River Glacier No.1, black carbon contributes approximately 10% to albedo reduction, causing radiative forcing up to 145 W/m^2. Overall, black carbon contributes more to glacier albedo reduction than dust [9]. Additionally, dissolved organic carbon content in Baishui River Glacier No.1 was estimated at 1.5 t, and inorganic particulate carbon at 7.25 t. The deposition of these light-absorbing impurities accelerates glacier ablation. As glaciers melt, stored carbon is released, transforming glaciers from “carbon sinks” to “carbon sources” [10].

4. Long-Term Monitoring, Experiments, and Research Results Effectively Serve Regional Sustainable Development

(1) Providing Technical Support for Tourism Safety, Landscape Beautification, and Water Resource Utilization

China’s first real-time glacier monitoring system has been established, enabling real-time monitoring of ice flow velocity and mass ablation of Baishui River Glacier No.1. This system can provide early warning for future ice collapse events [11]. Joint artificial snow enhancement experiments conducted with Lijiang Yulong County Meteorological Bureau in winter and spring have achieved remarkable results, playing a positive role in slowing Baishui River Glacier No.1 ablation. Using measured data and hydrological models, Baishui River glacier runoff depth datasets were reconstructed, quantifying the contribution rates of ice and snow meltwater to surface runoff and groundwater in temperate glacier basins [4,5], providing theoretical basis for regional water resource optimization.

(2) Revealing Glacier Tourism Service Value

Taking temperate glacier tourism service research as an entry point, the structure of glacier tourism source markets, tourism service value, and climate change impacts were revealed. The core tourism source market for ice and snow destinations has expanded from near-source markets in the initial development stage to far-source markets in the mature stage [12]. Using field surveys and the travel cost method, the service value of Yulong Snow Mountain glacier tourism was estimated at 2.033–5.718 billion yuan. In 2016, the value was only 1.8 billion yuan, close to the minimum estimated value, indicating substantial room for improvement in glacier tourism services. If ice and snow resources disappear, at least 20%–40% of tourists would be lost [13]. These research results provide theoretical basis for sustainable glacier tourism development in other destinations [14].

(3) Assessing Glacial Lake Outburst Flood Risks

Based on long-term monitoring of the temperate glacier-Midui Glacier, and integrating field investigations, multi-source imagery, UAVs, unmanned boats, and other multi-technical methods, the mechanisms of typical glacial lake outburst were systematically revealed, and early warning and mid-to-late disaster prevention and mitigation plans were proposed. The 1988 Guangxie Co outburst was mainly caused by internal water system collapse and glacier advance [15], while the 2020 Jiwenco glacial lake outburst in Jiali County resulted from multiple factors including ice and snow avalanche bodies, lateral moraine slope instability, landslide bodies, and continuous rainfall in the area before the outburst [16]. Based on this, the disaster risk of potentially dangerous glacial lake outbursts on the Qinghai-Tibetan Plateau was comprehensively assessed. It is recommended to strengthen positioned monitoring of temperate glacier-glacial lake interaction mechanisms and promptly implement engineering measures such as flood discharge to reduce the outburst risk of high-risk glacial lakes [17].

5. Conclusion

Based on long-term positioned monitoring and data accumulation, guided by cryospheric science, Yulong Snow Mountain Station has actively explored collaborative research pathways between the cryosphere and sustainable development, achieving significant progress in cryosphere change processes and mechanisms, hydrological and water resource effects, ecological effects, climate effects and impacts, and cryosphere-sustainable development research. The results have actively promoted and facilitated the formation and development of cryospheric science sub-disciplines including cryospheric chemistry, cryospheric microbiology, cryospheric tourism, cryospheric disaster science, and cryospheric humanities and sociology [18-20].

In the future, Yulong Snow Mountain Station plans to utilize high-tech methods, based on the station's observation network, to continuously strengthen long-term monitoring of temperate glaciers and their environment, expand collaborative research between the cryosphere and sustainable development, and focus on three major fields: cryosphere change processes and mechanisms, environmental effects of cryosphere change, and cryosphere-sustainable development. Taking key scientific issues of cryosphere change and sustainable development as entry points, the station will comprehensively assess the beneficial and hazardous effects of the cryosphere at different spatiotemporal scales to propose sustainable development pathways for cryosphere-affected regions.

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Author Information

Wang Shijin is a Research Professor at the State Key Laboratory of Cryospheric Science and Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences; Director of the Yulong Snow Mountain National Field Observation and Research Station for Cryosphere and Sustainable Development; and Board Member of the China Society of Cryospheric Science. His research focuses on cryosphere and sustainable development. E-mail: wangshijin@lzb.ac.cn

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