Reconstruction of Annual Glacier Mass Balance in the Qilian Mountains, 1961-2013 (Postprint)

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Abstract

Based on the Second Chinese Glacier Inventory data, precipitation data from the National Tibetan Plateau Science Data Center, measured air temperature data from meteorological stations, and a Digital Elevation Model, a distributed degree-day model incorporating a radiation term was employed. Using existing monitored glacier data as a basis to obtain degree-day factors and through parameter optimization, the glacier mass balance change series at the watershed scale in the Qilian Mountains from 1961-2013 was reconstructed. The results indicate that glacier mass balance changes in the Qilian Mountains can be divided into two stages with 1995 as the boundary. During 1961-1995, the glacier mass balance in the Qilian Mountains showed alternating positive and negative changes with small amplitude, and glacier ablation and accumulation were essentially balanced, with an average mass balance of (0.11$±0.13) m w.e. · a{-1}. During 1996–2013, glacier ablation intensified rapidly, and the mass balance remained consistently negative, with an average mass bal
1}; the main reason was that the year-by-year increase in positive accumulated temperature led to intensified glac
m w.e., and spatially, the glacier ablation rates in the central and eastern Qilian Mountains watersheds were greater than those of glaciers in the western section.

Full Text

Reconstruction of Annual Glacier Mass Balance in the Qilian Mountains from 1961 to 2013

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Abstract: Glacier mass balance, as a product of climate, directly influences glacier terminus position, area, ice storage, and runoff. With climate warming, most glaciers worldwide have experienced retreat, with an accelerating trend in recent decades. Under the 1.5°C climate scenario, Asian high mountain glacier storage is projected to be only 64%$±$7% of current levels by the end of the 21st century. Mountain glaciers serve as vital freshwater resources, playing crucial roles in agricultural water supply, hydropower, aquatic ecosystems, and basic water provision, particularly in arid and semi-arid regions where summer meltwater constitutes the primary river recharge. The glacierized area of the Qilian Mountains functions as a "wet island" for the arid and semi-arid Qaidam Basin and Hexi Corridor, making monitoring and estimation of glacier mass balance changes critical for these regions.

This study reconstructs the annual mass balance series for Qilian Mountain glaciers at the watershed scale from 1961 to 2013 using a distributed degree-day model enhanced with radiation terms. Based on China' s Second Glacier Inventory data, precipitation data from the National Tibetan Plateau Data Center, measured temperature data from meteorological stations, and digital elevation models, we optimized model parameters using monitoring data from reference glaciers to determine degree-day factors. Results indicate that glacier mass balance changes in the Qilian Mountains can be divided into two distinct periods at 1995. From 1961 to 1995, mass balance exhibited alternating positive and negative values with small fluctuations, as accumulation and ablation remained roughly equivalent, yielding an average mass balance of $(-0.11\$\pm0.13) mw.e. \cdot a^{\{-1\}.From 1996 to 2013, glacier ablation intensified rapidly, with consistently negative mass balance averaging (-0.54\pm0.13) mw.e. \cdot a}$ {-1}$, primarily due to rising positive accumulated temperatures accelerating melt.

The cumulative mass balance for Qilian Mountain glaciers from 1961 to 2013 was (−12.76$±$4.24) m w.e. Spatially, ablation rates in the central and eastern Qilian Mountains exceeded those in the western region.

Keywords: Qilian Mountains; watershed; glacier mass balance; reconstruction

1 Study Area Overview

The Qilian Mountains are located on the northeastern edge of the Tibetan Plateau [Figure 1: see original paper], extending approximately 800 km from Wushaoling in the east to the Dangjin Pass in the west, bordered by the Qaidam Basin to the south and the Hexi Corridor to the north. The region experiences a plateau continental climate, with the eastern section influenced by southeast and southwest monsoons and the western section controlled by westerly circulation. During winter, the area is dominated by the Mongolian High, resulting in cold, dry conditions, while summer brings combined influences from the Indian Ocean southwest monsoon and Pacific southeast monsoon. Mean annual temperature is below 0°C, with annual precipitation ranging 250–700 mm, concentrated in summer (accounting for 60-80% of annual totals) and decreasing from southeast to northwest.

According to the Second Chinese Glacier Inventory, the Qilian Mountains contain 2,694 glaciers covering 1,597.81 $\pm 70.3 km^{2}$, with ice storage of $84.48 \pm 3.13 km$ {3}, concentrated in high−altitude zones above 4,800–5,200 m [Figure 2: see original paper]. The Shule River basin hosts the most numerous (9
valley glacier that serves as the first glacier monitoring station in China and the reference glacier for parameter optimization in this study. The Bayin River basin has the fewest glaciers (5) and smallest area (0.18 km^2, 0.01% of total).

2 Methods

2.1 Distributed Degree-Day Model

The distributed degree-day model calculates glacier mass balance as:

$$MB = PDD \times DDF + a \times r + b$$

where MB is annual glacier mass balance (mm w.e.), PDD is positive accumulated temperature (°C · d), DDF is the degree-day factor (mm w.e. · $°C^{-1} \cdot d^{-1}$), P is solid precipitation (mm w.e.), a and b are radiation factors, and r is the average annual shortwave radiation across all grid cells on the glacier surface ($W \cdot m^{-2}$).

2.1.2 Shortwave Radiation Model The shortwave radiation model follows Kumar et al. [33], accounting for latitude, elevation, slope, aspect, and surface albedo, comprising direct, diffuse, and reflected radiation components.

Direct Radiation: Solar radiation attenuates through the atmosphere. Assuming clear skies, Beer-Lambert law applies:

$$I_b = I_0 \times e^{(-kM)}$$

where I_b and I_0 are radiation at the surface and top of atmosphere ($W \cdot m^{-2}$), k is the absorption constant, and M is air mass ratio. Solar altitude angle (α) is calculated as:

$$\sin \alpha = \sin \delta_s \sin L + \cos \delta_s \cos L \cos h_s$$

with δ_s as solar declination, L as latitude, and h_s as solar hour angle. For inclined surfaces, potential solar radiation (I_s) is:

$$I_s = I_0 \times \tau_b \times \cos i$$

where τ_b is atmospheric transmissivity (0.56–0.60 for clear skies) and i is the incidence angle between surface normal and solar direction.

Diffuse Radiation: Calculated using the isotropic sky model:

$$I_d = I_0 \times \tau_d \times \cos^2(\beta/2)$$

where τ_d is the diffuse transmissivity coefficient (0.217–0.249) and β is slope angle.

Reflected Radiation: Depends on surface tilt and ground reflectance:

$I\_r = I\_0 \times \tau\_r \times \sin^2(\beta/2) \times r$

where τ_r is the reflection coefficient (0.217-0.706) and r is ground reflectance.

2.2 Data and Processing

Model inputs include: (1) China' s Second Glacier Inventory dataset from the National Cryosphere Desert Data Center; (2) monthly precipitation dataset for China' s alpine regions (1954-2014) from the National Tibetan Plateau Data Center, resampled to 1,000 m resolution in ArcGIS; (3) temperature data from national meteorological stations and Laohugou Glacier No. 12; (4) measured mass balance data primarily from Laohugou Glacier No. 12 and Qiyi Glacier.

2.3 Model Parameter Calibration

Positive accumulated temperature was linearly extrapolated to glacier grids based on automatic weather station observations versus elevation (Figure 3). Considering spatial heterogeneity, the Qilian Mountains were divided into western, central, and eastern sections with lapse rates of −1.08, −1.02, and −1.15°C• m^{-1}, respectively. Temporal relationships were established with representative stations (Yumen, Yeniugou, Wushaoling, Dachaidan, Jiuquan, Menyuan, Lenghu).

Degree-day factors were calibrated using measured data: linear relationships with elevation were established from Laohugou Glacier No. 12 for all basins except the Beida River basin, which used Qiyi Glacier data (Table 2). Radiation factors were assumed constant spatially and temporally, optimized using Laohugou Glacier No. 12 data with a = 0.0025 and b = 0.5.

2.4 Model Error Analysis

Primary error sources include input data and parameter uncertainties. Model sensitivity was analyzed by varying positive accumulated temperature (\$±20±10±1$mmw.e. \cdot °C^{\{-1\} \cdot d}${-1}\$). Total simulation error equals the sum of these three error components.

3 Results

3.1 Glacier Mass Balance Changes

Simulations show a distinct shift in 1995. From 1961-1995, mass balance alternated between positive and negative with small amplitude, averaging (−0.11\$±0.13)$mw.e. \cdot a$^{-1}\$ as accumulation and ablation remained roughly balanced. From 1996-2013, rapid intensification of ablation produced consistently negative mass balance averaging (−0.54\$±0.13)$mw.e. \cdot a$^{-1}\$, driven by rising positive accumulated temperatures.

The cumulative mass balance from 1961–2013 was (−12.76$±4.24)*mw.e.Spatially, centralandeasternQilianMo*
seeoriginalpaper].TheBayinRiverbasinexhibitedthefastestmassbalancedeclineat(−24.9±0.22)*mmw.e.*·
a{-1}*, whiletheYuka − Tatalengbasinshowedtheslowestat*(−3.9±0.04)*mmw.e.* · *a*{-1}$ [Figure 3: see original paper].

Cumulative mass balance varied by basin: Bayin River (−35.1$±11.6*mw.e.*), *HalasuRiver*(−26.8±7.95*mw.e.*), *c*
a{-1})*andslowwarming*(0.64°*C* · *a*{-1}$). Shiyang, Halteng, and Beida River basins shifted from positive to negative balance in the 1990s, while Datong River basin transitioned in 2001 [Figure 5: see original paper].

3.2 Model Validation and Comparison

Comparison with stake measurements at Laohugou Glacier No. 12 showed strong agreement: simulated mass balance for 2009–2013 was −0.33 m w.e. versus measured −0.31 m w.e. (RMSE = 0.08 m w.e.) [Figure 7: see original paper]. Qiyi Glacier simulations also captured observed trends well (RMSE = 0.13 m w.e.), though slightly overestimating 2000s values. Comparison with ground-penetrating radar measurements (−7.99 m w.e. for 2000–2012) showed close correspondence with our results.

Our reconstruction compared favorably with previous studies [Figure 8: see original paper]. Relative to Liu et al. [25], our cumulative mass balance was lower pre-1990s but similar post-1990s, consistent with differences in data sources and parameterization. Comparison with geodetic method results for 2000–2010 [Figure 9: see original paper] confirmed our basin-scale estimates fell within measurement uncertainties across all basins.

4 Discussion and Conclusions

The 1995 regime shift in Qilian Mountain glacier mass balance aligns with numerous regional studies [25,43-44]. The 1961–1995 period of near-equilibrium reflected weak warming trends and significant precipitation increases that compensated for enhanced melt. Post-1995, pronounced warming combined with precipitation declines drove rapid mass loss.

The distributed degree-day model with radiation terms effectively reproduced spatial and temporal mass balance patterns. Degree-day factors, calibrated against measured data from reference glaciers, improved upon conventional constant values. However, limitations remain: (1) insufficient representative measured data may introduce bias; (2) temporal constancy of degree-day factors ignores effects of increasing glacier impurities that would enhance melt; (3) use of static glacier outlines from the Second Inventory neglects area and elevation changes, potentially overestimating mass balance.

Despite these limitations, model validation against in-situ measurements and geodetic methods confirms its ability to reproduce historical mass balance variations, providing essential boundary conditions for glacier hydrology modeling and supporting sustainable water resource management in western China under cryospheric change.

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References

[1] Zhang Guofei. Study on Mass Balance and Its Relationship with Climate Change of Urumqi Glacier No. 1 in Tianshan Mountains, China[D]. Lanzhou: Northwest Normal University, 2014.

[2] Liu Yushuo, Qin Xiang, Zhang Tong, et al. Variation of the Ningchanhe River Glacier No. 3 in the Lenglongling range, East Qilian Mountains[J]. Journal of Glaciology and Geocryology, 2012, 34(5): 1031-1036.

[3] Pu Jianchen, Yao Tandong, Duan Keqin, et al. Mass balance of the Qiyi Glacier in the Qilian Mountains: A new observation[J]. Journal of Glaciology and Geocryology, 2005, 27(2): 199-204.

[4] Kaser G, Fountain A, Jansson P. A Manual for Monitoring the Mass Balance of Mountain Glaciers[M]. Paris: Unesco, 2003.

[5] Zhang Y, Liu S, Shangguan D, et al. Thinning and shrinkage of Laohugou No. 12 glacier in the Western Qilian Mountains, China, from 1957 to 2007[J]. Journal of Mountain Science, 2012, 9(3): 309-317.

[6] Aizen V B, Kuzmichenok V A, Surazakov A B, et al. Glacier changes in the central and northern Tien Shan during the last 140 years based on surface and remote sensing data[J]. Annals of Glaciology, 2006, 43: 202-213.

[7] Yao T, Thompson L, Yang W, et al. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings[J]. Nature climate change, 2012, 2(9): 663-667.

[8] Schaner N, Voisin N, Nijssen B, et al. The contribution of glacier melt to streamflow[J]. Environmental Research Letters, 2012, 7(3): 034029.

[9] Radi V, Bliss A, Beedlow A C, et al. Regional and global projections of twenty first century glacier mass changes in response to climate scenarios from global climate models[J]. Climate Dynamics, 2014, 42(1-2): 37-58.

[10] Braithwaite R J, Zhang Y. Modelling changes in glacier mass balance that may occur as a result of climate changes[J]. Geografiska Annaler: Series A, Physical Geography, 1999, 81(4): 489-496.

[11] Liu Shiyin, Shen Yongping, Sun Wenxin, et al. Glacier variation since the maximum of the little ice age in the western Qilian Mountains, Northwest

China[J]. Journal of Glaciology and Geocryology, 2012, 24(3): 227-233.

[12] Yang Zhenniang. Glacier water resources in Qilian Mountains[J]. Journal of Glaciology and Geocryology, 1988, 4(1): 36-46.

[13] Cao Bo, Pan Baotian, Gao Hongshan, et al. Glacier variation in the Lenglongling range of eastern Qilian Mountains from 1972 to 2007[J]. Journal of Glaciology and Geocryology, 2010, 32(2): 242-248.

[14] Sun Meiping, Liu Shiyin, Yao Xiaojun, et al. Glacier changes in the Qilian Mountains in the past half century: Based on the revised first and second Chinese glacier inventory[J]. Acta Geographica Sinica, 2015, 70(9): 1402-1414.

[15] Gao Yongpeng, Yao Xiaojun, An Lina, et al. Change of ice volume in the Qilian Mountains during the period from 2000 to 2010[J]. Arid Zone Research, 2018, 35(2): 325-333.

[16] Gao Xin, Zhang Shiqiang, Ye Baisheng, et al. Recent changes of glacier runoff in the Hexi Inland river basin[J]. Advances in Water Science, 2011, 22(3): 344-350.

[17] Wang R, Liu S, Shangguan D, et al. Spatial heterogeneity in glacier mass balance sensitivity across high Mountain Asia[J]. Water, 2019, 11(4): 776.

[18] Wang Sheng, Pu Jianchen, Wang Ninglian. Study of mass balance and sensibility to climate change of Qiyi glacier in Qilian Mountains[J]. Journal of Glaciology and Geocryology, 2012, 33(6): 1214-1221.

[19] Hock R. Temperature index melt modelling in mountain areas[J]. Journal of Hydrology, 2003, 282(1): 104-115.

[20] Shangguan D, Liu S, Ding Y, et al. Changes in the elevation and extent of two glaciers along the Yanglonghe River, Qilian Shan, China[J]. Journal of Glaciology, 2010, 56(196): 309-317.

[21] Kang Shichang, Guo Wanqin, Wu Tonghua, et al. Cryospheric changes and their impacts on water resources in the Belt and Road Regions[J]. Advances in Earth Science, 2020, 35(1): 1-17.

[22] You Lianyuan, Yang Jingchun. Geomorphology of China[M]. Beijing: Science Press, 2013.

[23] Wu Guanghe, Xie Zichu, Huang Maohuan, et al. Study on the principal of present glaciers in Qilianshan[J]. Journal of Lanzhou University, 1980, 24(3): 127-134.

[24] Liu Shiyin, Guo Wanqin, Xu Junli. The Second Glacial Catalogue Data Set of China[DB/OL]. National Cryosphere Desert Data Center, 2019.

[25] Liu Shiyin, Yao Xiaojun, Guo Wanqin, et al. The contemporary glaciers in China based on the second Chinese glacier inventory[J]. Acta Geographica Sinica, 2015, 70(1): 3-16.

[26] Chen R, Liu J, Kang E, et al. Precipitation measurement intercomparison in the Qilian Mountains, north eastern Tibetan Plateau[J]. The Cryosphere, 2015, 9(5): 1995-2008.

[27] Chen R S, Song Y X, Kang E S, et al. A cryosphere hydrology observation system in a small alpine watershed in the Qilian Mountains of China and its meteorological gradient[J]. Arctic, Antarctic, and Alpine Research, 2014, 46(2): 505-523.

[28] Chen Rensheng, Liu Junfeng. China Alpine Region Month Precipitation Dataset (CAPD) (1954-2014)[DB/OL]. National Tibetan Plateau Data Center, 2017. DOI: 10.3990/CAPD.306.2016.db.

[29] Han C, Chen R, Liu Z, et al. Cryospheric hydrometeorology observation in the Hulu catchment (CHOICE), Qilian mountains, China[J]. Vadose Zone Journal, 2018, 17(1): 1-18.

[30] Liu Yushuo, Qin Xiang, Zhang Tong, et al. Variation of the Ningchan River Glacier No.3 in the Lenglongling rang, East Qilian Mountains[J]. Journal of Glaciology and Geocryology, 2012, 34(5): 1031-1036.

[31] Zhang X, Qin X, Xu C, et al. Simulation of runoff and glacier mass balance and sensitivity analysis in a glacierized basin, north eastern Qinhai Tibetan Plateau, China[J]. Water, 2018, 10(9): 1259.

[32] Huintjes E, Li H, Sauter T, et al. Degree day modelling of the surface mass balance of Urumqi Glacier No. 1, Tian Shan, China[J]. The Cryosphere Discussions, 2010, 4(1): 207-232.

[33] Kumar L, Skidmore A K, Knowles E. Modelling topographic variation in solar radiation in a GIS environment[J]. International Journal of Geographical Information Science, 1997, 11(5): 475-497.

[34] Gates D M. Biophysical Ecology[M]. New York: Dover Publications, 2012.

[35] Kreith F, Kreider J F. Principles of Solar Engineering[M]. Washington: Taylor & Francis, 1978.

[36] Liu B Y H, Jordan R C. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation[J]. Solar Energy, 1960, 4(3): 1-19.

[37] Xu Chunhai, Li Zhongqin, Wang Feiteng, et al. Estimation of mass balance of Shiyi Glacier in the Heihe River Basin, Qilian Mountains during 2000-2012 based on LiDAR and SRTM DEM[J]. Journal of Natural Resources, 2017, 32(1): 88-100.

[38] Fang Xiaoyu, Li Zhongqin, Gao Shu, et al. Physical energy balance and statistical glacier melting models comparison and testing for Shiyi Glacier, Heihe River Basin, Qilian Mountains, China[J]. Journal of Glaciology and Geocryology, 2015, 37(2): 336-350.

[39] Wang Panpan, Li Zhongqin, Wang Puyu, et al. Changes in the mass of Arctic Alpine glacier and its response to climate change[J]. Arid Zone Research, 2020, 37(5): 1205-1214.

[40] Bie Qiang, Qiang Wenli, Wang Chao, et al. Monitoring glacier variation in the upper reaches of the Heihe River based on remote sensing in 1960-2010[J]. Journal of Glaciology and Geocryology, 2013, 35(3): 574-582.

[41] Chen Hui, Li Zhongqin, Wang Puyu, et al. Change of glaciers in the central Qilian Mountain[J]. Arid Zone Research, 2013, 30(4): 588-593.

[42] Braithwaite R J, Raper S C B, Candela R. Recent changes (1991-2010) in glacier mass balance and air temperature in the European Alps[J]. Annals of Glaciology, 2013, 54(63): 139-146.

[43] Azam M F, Wagnon P, Vincent C, et al. Reconstruction of the annual mass balance of Chhota Shigri glacier, Western Himalaya, India, since 1969[J]. Annals of Glaciology, 2014, 55(66): 69-80.

[44] Cong Z, Kang S, Gao S, et al. Historical trends of atmospheric black carbon on Tibetan Plateau as reconstructed from a 150-year lake sediment record[J]. Environmental Science & Technology, 2013, 47(6): 2579-2586.

[45] Aizen V B, Kuzmichenok V A, Surazakov A B, et al. Glacier changes in the Tien Shan as determined from topographic and remotely sensed data[J]. Global and Planetary Change, 2007, 56(3-4): 328-340.

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