Postprint: Monitoring Glacier Changes in Yilianhabierga Based on Sentinel-2

Authors: Li Ruonan, Li Junli, Li Shuangshuang, Liu Shuaiqi, Du Weibing

Date: 2024-07-04T00:00:00+00:00

Abstract

High-resolution temporal remote sensing plays an important role in monitoring glacier changes. This study utilizes 2016–2022 Sentinel-2 multi-temporal satellite imagery and a D-UNet semantic segmentation model to extract glacier change information for the Yilianhabierga Glacier, compares these results with extraction results from temporally proximate Landsat remote sensing data, and evaluates the accuracy differences between Sentinel-2 and Landsat for glacier mapping. Based on this, 75 typical glaciers were selected to analyze recent variation characteristics of total glacier area and glacier termini in the study area. The results show that: (1) The overall accuracy of Sentinel-2 glacier mapping is 95.0%, which is 5%–10% higher than Landsat-8 under the same conditions. (2) The annual average area retreat rate of glaciers in the study area from 2016–2022 is 0.75% $\pm$ 0.69%, wherein areas below 4600 m elevation experienced glacier area reduction, with lower elevations exhibiting greater area retreat rates. (3) Over the recent 6 years, the average elevation of the termini of 75 typical glaciers increased by 17.75 m, and the length retreated at an average rate of 11.39 $\pm$ 2.36 m · a-1, with the most significant retreat occurring in the west, northeast, and south aspects, at rates of 15.49 $\pm$ 2.36 m · a-1, 13.95 $\pm$ 2.36 m · a-1, and 13.14 $\pm$ 2.36 m · a-1, respectively. The glacier terminus retreat rate decreases with increasing elevation.

Full Text

Monitoring Glacier Changes in Yilian Habirga Mountain Using Sentinel-2 Data

Li Ruonan[123], Li Junli[13], Li Shuangshuang[14], Liu Shuaiqi[123], Du Weibin[4]

[1]State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, Xinjiang 830011,

China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Key Laboratory of GIS & RS Application, Xinjiang Uygur Autonomous Region, Urumqi, Xinjiang 830011, China
[4]College of Survey and Territory Information Engineering, Henan Polytechnic University, Jiaozuo, Henan 454003, China

Abstract

High-resolution time-series remote sensing plays a vital role in monitoring glacier changes. This study utilizes Sentinel-2 multitemporal satellite imagery and a semantic segmentation model to extract glacier change information in the Yilian Habirga region, comparing the results with those derived from temporally proximate Landsat data to evaluate accuracy differences in glacier mapping. Based on these findings, 75 typical glaciers were selected to analyze recent variations in total glacier area and terminus characteristics. The results demonstrate that: (1) The overall accuracy of Sentinel-2 glacier mapping is 95.0%, which is 5%-10% higher than Landsat-8 under equivalent conditions. (2) The average annual area retreat rate of glaciers in the study area from 2016 to 2022 was 0.75%$±0.69{-1}, withthemostsignificantreductionsoccurringbelow4600melevation; loweraltitudesexhibitedgreaterarearetreatrat
1}.Themostpronouncedretreatsoccurredinthewestern, northeastern, andsouthernaspects, withratesof15.49±
1}, and13.14±2.36ma^{-1}$, respectively. Glacier terminus retreat rates decreased with increasing altitude.

Keywords: glacier terminus; deep learning; spatiotemporal variation; Sentinel-2; Yilian Habirga Mountain

Introduction

In the context of global warming, glacier mass loss has shown an accelerating trend. Measurements of these changes primarily employ metrics such as glacier length, elevation, area, volume, and surface flow velocity. The glacier tongue represents the core zone of glacier accumulation and ablation, exhibiting the most significant area and volume changes with notable impacts on regional environment and ecology. Obtaining precise and temporally comprehensive glacier change information is crucial for understanding glacier-climate relationships, recognizing glacier mass balance, and predicting glacier hazards.

Research on glacier changes over recent decades indicates that most mountain glaciers worldwide are in retreat, with this retreat showing an accelerating trend. However, significant regional differences exist in glacier retreat, requiring increasing attention to regional variations and mechanistic analyses. Previous studies have primarily utilized remote sensing data including Landsat, ASTER, and SPOT-5, employing mapping methods such as thresholding, ratio methods, and object-oriented classification. These semi-automated approaches used monitoring indicators encompassing glacier area, retreat length, and ice thickness.

The phenomenon of widespread glacier retreat is globally prevalent, primarily driven by climatic factors such as temperature rise, monsoons, and sea-level rise. Regional differences in glacier retreat result from variations in topography, glacier surface albedo, and atmospheric circulation. Xinjiang' s continental glaciers, in particular, often have extensive debris cover at their termini, whose spectral information interferes with and compromises the completeness of glacier boundary extraction. Studies show that interannual glacier retreat rates typically do not exceed 10 m a^{-1}, with regional average retreat amounts of 10.5 m a^{-1}. The most significant glacier area changes have been observed in the western Tianshan, Altai, and eastern Pamir regions.

The Tianshan Mountains in Xinjiang represent China' s most densely glacierized region with the highest frequency of ice-related hazards. Numerous scholars have analyzed glacier changes in the eastern Tianshan, Bogda Mountains, and other areas using remote sensing techniques, yet few studies have focused on glacier changes in the central Tianshan' s Yilian Habirga region.

1. Study Area and Data

1.1 Study Area Overview

The glaciers of the Yilian Habirga Mountain main peak region in the central Tianshan are located between 43°25 -44°10 N and 83°30 -85°05 E, extending from Lapate Ice Pass in the west through Akwuzen to Gurbenbieerke Ice Pass in the east, spanning Nileke, Wusu, and Shawan counties. This area constitutes the second-largest modern glacier distribution zone in the Chinese Tianshan and the largest glacierized watershed in northwestern Tianshan in terms of both quantity and scale. According to the Second Glacier Inventory, the study area contains numerous glaciers with higher concentration and larger individual areas. Only a few large glaciers exist, yet they account for a substantial proportion of the total glacier area. Glaciers are predominantly distributed at elevations of 3300–5000 m, with 3500 m marking the boundary between extremely high mountain and high mountain zones where modern glacial processes are exceptionally intense. This region serves as the source area for major rivers in central Tianshan, including the Manas, Kuitun, Kash, and Kunes Rivers, with a total glacier area of 582.81 km^2, representing 27.86% of the total glacier area in northwestern Tianshan.

1.2 Data Sources and Processing

The remote sensing imagery applied for glacier extraction in this study includes Sentinel-2 MSI and Landsat-8 OLI data, with local high-resolution domestic satellite imagery used for validation of Sentinel-2 glacier mapping accuracy. To minimize interference from snow cover, mountain shadows, clouds, and cloud shadows on glacier mapping, imagery from summer and autumn periods with high solar angles, significant snow melt, and minimal cloud cover was prioritized based on data availability. All Sentinel-2 and Landsat-8 data used in this study are Level-1C products that have undergone geometric correction and radiometric calibration, requiring only radiometric correction before mosaic and clipping to the study area. The selected primary remote sensing images are listed in .

The 30 m × 30 m ASTER Digital Elevation Model (DEM) data were obtained from the International Scientific Data Service Platform. Additionally, the *Concise Catalogue of Chinese Glaciers* and China's Second Glacier Inventory dataset were referenced as bases for glacier identification and to obtain glacier inventory attributes.

2. Glacier Information Extraction Method Based on Semantic Segmentation

Glacier identification and boundary extraction constitute the prerequisite for glacier change analysis. Glacier mapping based on optical remote sensing is affected not only by snow cover but also by debris cover, primarily because the spectral information from optical remote sensing cannot effectively identify ice bodies located beneath the surface and covered by debris. Therefore, this study extracts only glaciers located above the surface. Focusing on glaciers in the Yilian Habirga Mountain region, this research employs Sentinel-2 time-series data and the D-UNet semantic segmentation network to extract glacier information, analyzing the precision and efficiency of deep learning models for glacier mapping and comparing the mapping accuracy between the two satellite data sources.

2.1 D-UNet Network Model

The D-UNet network is an encoder-decoder structure that achieves image semantic segmentation and feature extraction through encoding and decoding processes. The network consists of a 4-layer encoder composed of downsampling layers and a 4-layer decoder composed of upsampling layers, with dense atrous convolution modules inserted between the encoder and decoder to form an end-to-end network. The encoder comprises convolutional layers and max pooling layers, while the decoder consists of upsampling layers. Deformable convolution blocks are employed at each encoding and decoding stage, enabling the network to adaptively adjust the receptive field according to object size and shape. This provides significant advantages for extracting glacier information with complex structures. The dense atrous convolution module expands the receptive field of feature maps, thereby improving segmentation accuracy to some extent.

2.2 Sample Preparation and Augmentation

Small-sample preparation and augmentation are critical for model training and validation. Here, 1024$×1024*pixelsampleimageswereextractedfromSentinel−*
2imageryacrossmultipleyearsinthestudyarea, coveringglaciersofdifferentmorphologiesandtypes, particula
coveredglacierswithsignificantspectralfeaturedifferencestoenhancemodelrecognitioncapability.Sampleim

colorcompositiontoincreasecontrastbetweenglaciersandotherfeatures.Samplelabelswereproducedusingacom
*seeoriginalpaper].Sampleimageswweresubsequentlycroppedto*256×$256 pixels, yielding 300 non-repetitive samples. Augmentation techniques including rotation, mirroring, blurring, and lighting adjustment were applied, expanding each sample image into 20 distinct, non-overlapping augmented images to enhance network robustness and generalization. A total of 6,000 augmented samples were obtained, with 5,000 designated as training samples and 1,000 as test samples.

2.3 Model Training and Prediction

Using Pytorch as the underlying deep learning framework, hyperparameters were configured and the model was trained with 5,000 training samples. The initial learning rate was set to 0.001 with a batch size of 8. During the encoding phase, downsampling operations were applied to input samples to obtain high-dimensional feature pyramids. In the decoding phase, upsampling operations were employed to restore image details and positional information, producing output images identical in size to input samples and determining the category of each pixel. Glacier and non-glacier pixel values were assigned as 1 and 0, respectively. The FocalLoss function was adopted as the loss function, with an exponential decay learning rate strategy and Adam optimizer. Training continued until the loss value fell below a specified threshold. Once trained, the model was applied to predict and simulate glacier extraction using the established test set, outputting glacier extraction results.

2.4 Accuracy Validation

Accuracy evaluation methods are based on comparative analysis between glacier identification results and visually interpreted glacier outlines. Using Sentinel-2 and Landsat-8 as base maps, multi-threshold optimal boundaries were combined with visual interpretation corrections to establish true values for assessing extraction accuracy. This study employs Producer' s Accuracy (PA), User' s Accuracy (UA), Overall Accuracy (OA), F1-score, and Intersection over Union (IoU) to evaluate deep learning model performance. PA represents the proportion of correctly classified glacier samples among total actual glacier samples, UA indicates the proportion of correctly classified glacier samples among total predicted glacier samples, OA shows the proportion of correctly classified samples among all samples, F1-score represents a harmonic mean of precision and recall, and IoU indicates the overlap between predicted glacier results and actual glacier extents.

2.5 Terminus Change Quantification and Uncertainty Assessment

Due to the heterogeneous surface characteristics of glaciers in the study area—clean ice and snow in the upper portions and debris-covered ablation zones in the lower portions—glacier terminus boundaries were manually edited through visual interpretation. The main axis method was employed: multiple line segments parallel to the longest axis were used to cut the glacier terminus, with the average change across each segment calculated as the glacier terminus change.

Uncertainty in glacier area and retreat calculations follows established formulas:

For glacier area error due to image spatial resolution:

$$E = N \times A$$

where E is the glacier area error caused by image spatial resolution (km^2), N is the perimeter of the glacier outline (km), and A is the area of half a pixel (km^2).

For glacier area change uncertainty:

$$\Delta A = \sqrt{A_1^2 + A_2^2}$$

where ΔA is the uncertainty in glacier area change (km^2), and A_1 and A_2 are the uncertainties in glacier area for two periods (km^2).

For terminus retreat uncertainty:

$$\Delta L = \frac{\sqrt{\left(\frac{a}{2}\right)^2 + \left(\frac{b}{2}\right)^2}}{Y}$$

where ΔL is the terminus change uncertainty (m a^{-1}), a is the pixel width (m), b is the pixel length (m), and Y is the number of years between the two terminus boundaries.

3. Results

3.1 Glacier Mapping and Accuracy Assessment

The mapping accuracy of glacier area extracted by the D-UNet model was evaluated using Sentinel-2 and Landsat-8 data. All accuracy metrics for the 10 m resolution Sentinel-2 data exceed those of Landsat-8, with Producer' s Accuracy and IoU improving by approximately 5%-10%. This demonstrates that under equivalent methodological conditions, increased resolution yields improved mapping accuracy. The spectral and visual characteristics of glacier termini differ substantially from glacier main bodies. Comparative analysis of temporally proximate Sentinel-2 and Landsat-8 extraction results, validated against domestic high-resolution GF-2 imagery, reveals that differences in glacier boundaries extracted from the two sensors average <10 m in high-elevation regions, but differences are more pronounced in glacier terminus zones [Figure 3: see original paper]. Sentinel-2 imagery can identify debris-covered glaciers, producing terminus boundaries with richer edge details and smoother lines, whereas Landsat-8 extracted terminus boundaries exhibit serrated patterns with over- or under-extraction phenomena. For example, at a glacier terminus at [location], Sentinel-2 extraction results align more closely with high-resolution imagery.

Superimposing multi-year glacier results reveals that Sentinel-2 can detect annual changes, while Landsat-8 typically requires 2–3 years to detect changes due to its coarser spatial resolution and more pronounced mixed-pixel phenomena, with lower distinguishability between debris and bare ground that can cause abrupt terminus boundary changes. Therefore, Sentinel-2 imagery enables more effective monitoring of glacier terminus changes.

3.2 Glacier Change Characteristics

Given that different glaciers under the same geographic location and climate environment exhibit varying responses, this study extracted terminus changes for 75 typical glaciers in the research area, analyzing overall trends and topographic factors (aspect and elevation).

3.2.1 Glacier Area Changes The total glacier area in Yilian Habirga Mountain was 546.86$±15.60km^{2}$ in [year] and 522.17$±16.52km^{2}$ in 2022, representing a reduction of 24.69$±22.72km^{2}$ with an average annual area retreat rate of 0.75%$±0.69^{-1}.Glaciersarepredominantlydistributedbetween3300–5300melevation, with3800–4500mcontaining
yet the area retreat rate reaches 34.93%.

Glaciers in all aspects exhibit area reduction and general retreat, with north-, northwest-, and west-facing glaciers showing the most significant retreat at rates of 7.52%, 6.30%, and 5.10%, respectively. East-, southeast-, and south-facing glaciers show lower retreat rates of 2.05%, 2.10%, and 1.93%, respectively.

3.2.2 Glacier Terminus Changes To further analyze terminus retreat variations, 75 typical glaciers were selected as primary study objects, with retreat lengths and rates calculated for different aspects [Figure 6: see original paper]. Based on study area data, glaciers were distributed across eight aspects: north, northeast, east, southeast, south, southwest, west, and northwest, with selected glacier quantities of [numbers] for each aspect. The main axis method was used to obtain retreat lengths for each glacier, with topographic factors (aspect and elevation) quantitatively analyzed.

Results indicate that the 75 glaciers exhibited an average terminus retreat rate of 11.39$±2.36ma^{-1}, withretreatconcentratedatglacieredgesandtermini.Averageretreatratesacrossaspectswere: west15.49±2.36m
1}, south13.14±2.36ma^{-1}, northeast13.95±2.36ma{-1}, north10.52±2.36ma^{-1}, andotheraspects < 10ma{-
1}$. The most significant retreats occurred in western, southern, and northeastern aspects.

Analysis of the 75 typical glaciers reveals that the average terminus elevation increased by 17.75 m over six years, with retreat rates decreasing as terminus elevation increased. The average terminus elevation is primarily distributed between 3500–3900 m, with elevation increases of 30.87 m, 33.00 m, and 16.09 m in the 3500–3600 m, 3600–3700 m, and 3700–3900 m ranges, respectively, demonstrating a slowing vertical growth trend during retreat at higher elevations.

4. Discussion

Improvements in spatial and temporal resolution significantly enhance glacier mapping capabilities. Compared with the commonly used Landsat series satellites, Sentinel-2' s 10 m spatial resolution and 2–3 day revisit cycle provide higher glacier boundary precision. This study' s results show terminus boundary changes >15 m can be detected almost annually, whereas Landsat' s temporal resolution often fails to detect changes within 2–3 years when retreat lengths are <10 m.

High-resolution remote sensing data can obtain more accurate glacier boundaries, but long revisit cycles and small coverage areas limit large-scale dynamic monitoring. For instance, domestic GF-2 imagery with a 69-day revisit period requires 4–5 scenes to cover the study area, and obtaining effective monitoring data often takes 1–2 years, hindering dynamic monitoring needs. Sentinel-2-based glacier monitoring not only achieves higher mapping accuracy than Landsat-8 for quantifying terminus and area changes over short periods but also offers high temporal resolution, enabling selection of imagery minimally affected by snow and shadows for more precise extraction of terminus and area changes, thereby shortening monitoring cycles.

Glacier terminus retreat in central Tianshan has shown accelerated retreat in recent decades. Studies indicate Xinjiang glaciers retreated at 0.27% a^{-1} during 1960–2009, with Tianshan glaciers retreating at 0.37% a^{-1} during 1960–2010. The Manas River basin east of the study area showed 0.48% a^{-1} retreat during 1964–2015, while the Kuitun River basin to the west showed 0.80% a^{-1} retreat during 1964–2015. This study' s finding of 0.75% a^{-1} retreat for Yilian Habirga glaciers during 2016–2022 shows consistent acceleration trends with neighboring regions.

From a terminus retreat perspective, the Kuitun River' s Hasilgan Glacier west of the study area retreated at 1.40 m a^{-1} during 1980–2009, while glaciers in the Manas River basin to the east retreated at 5.07 m a^{-1} during 1964–2015. This study' s Yilian Habirga glaciers retreated at 11.39 m a^{-1} during 2016–2022, indicating significantly increasing retreat rates over time. All aspects show general area reduction, with north- and west-facing glaciers showing fastest area reduction rates, and north-facing glaciers having much lower average elevations than south-facing ones. The proportion of small- and medium-sized glaciers increases from west to northwest to north, indicating that lower-elevation, smaller glaciers exhibit more significant area reduction. Western and southern aspects show highest length retreat rates, primarily because western glaciers in the study area are predominantly small, with selected typical glaciers also being small and thus exhibiting relatively larger terminus retreat rates, demonstrating poor stability of small glaciers.

5. Conclusion

The Sentinel-2-based glacier boundary extraction results demonstrate that all accuracy evaluation metrics exceed those of Landsat-8 by 5%–10%. Sentinel-2 segmentation is more accurate, with extracted boundaries more closely matching actual glacier margins.

From 2016 to 2022, Yilian Habirga Mountain glaciers showed an average annual area reduction rate of 0.75%\$±0.69$^{\{-1\}, with terminus retreat of 11.39\pm2.36 ma}${-1}\$. North-facing glaciers exhibited the most severe area reduction, while western, northeastern, and southern aspects showed fastest terminus retreat rates. Glacier terminus retreat rates decreased with increasing elevation.

Compared with neighboring glacier changes in central Tianshan, the terminus retreat trend is consistent, showing clear acceleration with significantly increased retreat rates and area reduction rates. Due to differences in glacier characteristics (type, surface morphology, scale) and terrain (aspect, elevation), terminus changes vary across different regions and even within the same region. Future research should conduct long-term monitoring of selected glaciers across different regions, combining climate, terrain, and glacier characteristics to analyze primary driving factors and understand terminus change processes and mechanisms.

References

[1] Kraaijenbrink P, Bierkens M, Lutz A, et al. Impact of a global temperature rise of 1.5 degrees Celsius on Asia’ s glaciers[J]. Nature, 2017, 549(7671): 257-260.

[2] Li Kaiming, Chen Shifeng, Kang Lingfen, et al. Comparative research on Chinese continental glacier and temperate glacier changes: Taking Urumqi glacier No.1 and Baishui glacier No.1 as example[J]. Arid Zone Research, 2018, 35(1): 12-19.

[3] Zhang Zhen. Study of glacier ice volume changes on the East Pamir Plateau based on remote sensing and GIS[J]. Acta Geodaetica et Cartographica Sinica, 2021, 50(7): 992.

[4] Wang Lihui, Qin Xiang, Chen Jizu, et al. Reconstruction of the glacier mass balance in the Qilian Mountains from 1961 to 2013[J]. Arid Zone Research, 2021, 38(6): 1524-1533.

[5] Du Weibing, Zhang Shiqiong, Li Junli, et al. Temporal reconstruction of alpine glacier surface elevation variation in Central Asia[J]. Arid Zone Research, 2022, 39(3): 676-683.

[6] Li Zhenlin, Qin Xiang, Wang Jing, et al. Remote sensing monitoring of Lenghuolongling glacier in the eastern Qilian Mountains from 2004 to 2015[J]. Science of Surveying and Mapping, 2018, 43(6): 45-51.

[7] Huai Baojuan, Li Zhongqin, Sun Meiping, et al. Discussion on RS methods for glacier outline detection: A case study in headwaters of the Kanas River[J]. Arid Zone Research, 2013, 30(2): 372-377.

[8] Poddar J, Pandey A C. Estimating the impact of changes in mass balance on variations in glacier area and snout fluctuations in Western Himalayas, J&K India[C]//2014 IEEE Geoscience and Remote Sensing Symposium. IEEE, 2014: 4034-4037.

[9] Li Zhongqin, Li Kaiming, Wang Lin. Study on the recent changes of glaciers in Xinjiang and their impact on water resources[J]. Quaternary Sciences, 2010, 30(1): 96-106.

[10] Kachouie N N, Gerke T, Huybers P, et al. Nonparametric regression for estimation of spatiotemporal mountain glacier retreat from satellite images[J]. IEEE Transactions on Geoscience and Remote Sensing, 2014, 53(3): 1135-1149.

[11] Singh A, Kumar R, Kumar R, et al. Quantification of volume loss and snout retreat from 1980 to 2019 of Baspa basin glaciers, western Himalaya[J]. Materials Today: Proceedings, 2022, 49: 3331-3339.

[12] Sivaranjani S, Priya G M, Vishnupant A K, et al. Study of dynamics in surface ice flow rate of glaciers in Hunza basin, Karakoram[J]. Environmental Science and Pollution Research International, 2023, 30(22): 62782-62802.

[13] Wang Zhongwu, Wang Zhipan, You Shucheng, et al. A context-aware semantic segmentation network approach for glacier extraction from Landsat images[J]. Acta Geodaetica et Cartographica Sinica, 2020, 49(12): 1575-1582.

[14] Jin Q, Meng Z, Tuan D Pham, et al. DUNet: A deformable network for retinal vessel segmentation[J]. Knowledge Based Systems, 2019, 178: 149-162.

[15] Peng Y, He J, Yuan Q, et al. Automated glacier extraction using a transformer based deep learning approach from multi-sensor remote sensing imagery[J]. ISPRS Journal of Photogrammetry and Remote Sensing, 2023, 202(1): 303-313.

[16] Du W, Li J, Bao A, et al. Mapping changes in the glaciers of the eastern Tienshan Mountains during 1977-2013 using multitemporal remote sensing[J]. Journal of Applied Remote Sensing, 2014, 8(1): 084683.

[17] Veettil K B, Bremer F U, Grondona B E A, et al. Recent changes occurred in the terminus of the Debris-covered Bilafond Glacier in the Karakoram Himalayas using remotely sensed images and digital elevation models (1978-2011)[J]. Journal of Mountain Science, 2014, 11: 398-406.

[18] Salerno F, Thakuri S, Tartari G, et al. Debris-covered glacier anomaly? Morphological factors controlling changes in the mass balance, surface area, terminus position, and snow line altitude of Himalayan glaciers[J]. Earth and Planetary Science Letters, 2017, 471: 19-31.

[19] Zhao Guining, Zhang Zhengyong, Liu Lin, et al. Changes in glacier material balance in the Manas River basin based on multi-source remote sensing data[J]. Acta Geographica Sinica, 2020, 75(1): 98-112.

[20] Liu Zhaohui, Qi Zhonghua. Research progress of Antarctic glacier monitoring based on optical image data[J]. Geomatics & Spatial Information Technology, 2022, 45(S1): 17-21.

[21] Lea J, Mair D, Rea B. Evaluation of existing and new methods of tracking glacier terminus change[J]. Journal of Glaciology, 2014, 60(220): 323-332.

[22] Wang Zhiwen. Research and Application of Semantic Segmentation of High-resolution Remote Sensing Images Based on Deep Learning[D]. Beijing: Beijing University of Posts and Telecommunications, 2019.

[23] Kaushik S, Singh T, Bhardwaj A, et al. Automated delineation of supraglacial debris cover using deep learning and multisource remote sensing data[J]. Remote Sensing, 2022, 14(6): 1352.

[24] Li Shanshan. Characteristics of Changes in Typical Glacier Termini and Their Spatial Differences in Different Regions of the Tianshan Mountains, China[D]. Lanzhou: Northwest Normal University, 2013.

[25] Wang Zifei, Ke Changqing. Deep learning based glacier recognition from Sentinel-1A imagery[J]. Remote Sensing Information, 2022, 37(4): 43-50.

[26] Nie Yong, Zhang Yili, Liu Linshan, et al. Remote sensing monitoring of glacier changes in Mount Everest National Nature Reserve in the past 30 years[J]. Acta Geographica Sinica, 2010, 65(1): 13-28.

[27] Li Shanshan, Zhang Mingjun, Li Zhongqin, et al. Changing characteristics of modern glacier termini in the Tianshan Mountains, China, 1960-2009[J]. Arid Zone Research, 2013, 30(2): 378-384.

[28] Onyejekwe O, Holman B, Kachouie N N. Multivariate models for predicting glacier termini[J]. Environmental Earth Sciences, 2017, 76: 1-10.

[29] Xing Wucheng, Li Zhongqin, Zhang Hui, et al. Spatial and temporal changes of glacier resources in the Tianshan Mountains of China since 1959[J]. Acta Geographica Sinica, 2017, 72(9): 1594-1605.

[30] Huang Xiaoran, Bao Anming, Guo Hao, et al. Typical glacier changes in the eastern section of the Tianshan Mountains in China in the last 20 a and its climate response[J]. Arid Zone Research, 2017, 34(4): 870-880.

[31] Tian Mengqi, Duan Keqin, Shi Peihong. Study of glacier changes on the Tibetan Plateau based on the Google Earth Engine platform: A case study of the Puruogangri Icefield[J]. Scientia Geographica Sinica, 2023, 43(6): 943-951.

[32] Du W, Shi N, Xu L, et al. Monitoring the spatiotemporal difference in glacier elevation on Bogda Mountain from 2000 to 2017[J]. International Journal of Environmental Research and Public Health, 2021, 18(12): 6374.

[33] Zhao Jingqi, Mansuer Shabiti, Mailikai Aimaiti, et al. Glacier changes in Tomur Peak National Nature Reserve from 2004 to 2017[J]. Arid Zone Research, 2020, 37(4): 1079-1086.

[34] Xiaobing, Yan Lili, Xu Jinghua, et al. Analysis of glacier changes in the Manas River basin in the last 50 a based on multi-source data[J]. Journal of Glaciology and Geocryology, 2015, 37(5): 1188-1198.

[35] Wu Kunpeng, Liu Shiyin, Zhu Yu, et al. Dynamic monitoring of surface elevation at the end of Mingyong Glacier in Meili Snow Mountain based on UAV photogrammetry[J]. Progress in Geography, 2021, 40(9): 1581-1589.

[36] Shi Yafeng, Wang Zongtai, Liu Chaohai, et al. Concise Catalogue of Chinese Glaciers[M]. Shanghai: Shanghai Popular Science Press, 2005: 194.

[37] Liu Shiyin, Guo Wanqing, Xu Junli. The second glacial catalogue data set of China (V1.0)[DB/OL]. National Cryosphere Desert Data Center, 2019.

[38] Tiang Hao. Study on the Geometrical Characteristics and Stability of Glaciers in the Manas River Basin[D]. Shihezi: Shihezi University, 2022.

[39] Du Weibing, Li Junli, Bao Anming, et al. Information extraction method of alpine glaciers with multitemporal and multiangle remote sensing[J]. Acta Geodaetica et Cartographica Sinica, 2015, 44(1): 59-66.

[40] Jiao Keqin, Jing Zhefan, Cheng Peng, et al. Analysis of the monitoring results of glacier change in the Kuitun River Hasilgan 51, Tianshan Mountain[J]. Arid Zone Geography, 2009, 32(5): 733-740.

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