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Degradation of the Glaciers of the Western and Central Tien Shan: Spatio-Temporal Trends and Factors (according to Remote Sensing of the Earth)

This article presents a comparative analysis of mountain glacier degradation in the Western and Central Tien Shan under contemporary climate warming. The study aims to identify regional differences in the rate and patterns of glacier change, taking into account morphological characteristics, slope aspect, and orographic conditions. The analysis is based on data from the USSR Glacier Inventory, the Kyrgyzstan Glacier Inventory, Earth observation imagery (Landsat and Sentinel), as well as published and original research findings for glaciers in the Pskem River Basin. The methodological framework combines GIS-based spatial analysis, morphological glacier classification, and a comparative assessment of spatio-temporal changes in glacier area. The results indicate that glaciers in the Western Tien Shan exhibit greater sensitivity to climatic forcing and undergo more rapid degradation, accompanied by glacier fragmentation and pronounced spatial differentiation. In contrast, glacier change in the Central Tien Shan is more gradual and is expressed primarily through ice-thickness reduction and the progressive retreat of the termini of large valley glaciers. These findings highlight the importance of morphological and orographic controls in shaping regional patterns of glacier degradation and can inform assessments of ongoing and future changes in water resources across the mountain regions of Central Asia.

Keywords: glacier dynamics; glacier systems, glacier degradation, Western Tien Shan, Central Tien Shan, climate change, remote sensing, GIS-based spatial analysis, water resources.

Introduction

Mountain glaciers of the Tien Shan constitute one of the key components of natural geosystems in Central Asia and play a fundamental role in shaping the regional hydrological regime. Under arid and semi-arid climatic conditions, glacier meltwater provides a critical contribution to river discharge, supports the relative stability of water availability, governs the seasonal structure of runoff, and directly influences the socio-economic development of mountain and piedmont areas. A substantial share of river flow in the Chu, Talas, Naryn, Chatkal, and Pskem basins is generated by melt from mountain glaciers, which makes their current state a matter of high scientific and practical significance—particularly in the context of increasing regional water scarcity.

In recent decades, steady trends in the degradation of mountain glaciers have been observed in the Tien Shan due to rising average annual and summer air temperatures, changes in precipitation patterns and the composition of phases, as well as an increase in the net energy balance of the land surface. These processes are expressed in a reduction of glacier area and volume, thinning of ice cover, fragmentation of glacier bodies, and transformations in glacier morphology. In contemporary science, glacier degradation is widely regarded as one of the most visible and sensitive indicators of climate change and is accompanied by substantial modifications of hydrological regimes, including decreased stability of summer runoff, increased intra-seasonal variability of water resources, and heightened hydrological risks.

The issue of glacier degradation is especially acute in the Tien Shan due to pronounced regional heterogeneity of natural conditions, including differences in orographic structure, altitudinal zonation, slope aspect, and climatic characteristics. The Western and Central Tien Shan differ in glacier morphometric properties, accumulation and ablation conditions, and the degree of sensitivity to recent climatic changes (Fig. 1). In the Western Tien Shan, glaciers are generally smaller, have lower accumulation-zone elevations, and exhibit stronger related differentiation, which collectively increases their vulnerability to warming. By contrast, the Central Tien Shan is characterized by larger valley glaciers with thick ice bodies and a more inertial mode of response to climatic forcing.

Despite the substantial body of research on Tien Shan glacier dynamics, the scientific literature still provides an incomplete characterization of regional differences in the rates, directions, and mechanisms of glacier degradation, as well as the role of morphological and orographic controls in shaping these differences. Many studies remain limited either to individual basins or to generalized assessments of glacier area change that do not account for glacier morphological structure and slope-aspect effects, thereby reducing the predictive value of the derived results.

In this context, an integrated comparative analysis of glacier degradation in the Western and Central Tien Shan using Earth observation data and GIS techniques is particularly important (Figs. 2-3). The combination of satellite imagery (Landsat, Sentinel) with glacier inventory records and field-based research enables the identification of spatio-temporal patterns of glacier transformation, the evaluation of morphological and orographic controls, and the refinement of region-specific glacier responses to contemporary climate warming.

The objective of this study is to identify and analyze regional differences in the degradation of mountain glaciers in the Western and Central Tien Shan under ongoing climate change, taking into account glacier morphological structure, slope-aspect characteristics, and orographic conditions. The results are important for assessing the resilience of water resources in the mountain regions of Central Asia and for developing scientifically grounded approaches to projecting hydrological change under continued climatic warming [1–5].



Figure 1. Geographic location of the research area

Over the past decades, the Tien Shan has exhibited persistent and statistically significant trends of mountain glacier degradation driven by the combined effects of regional warming, shifts in the seasonal distribution of precipitation, and enhanced radiative-energy forcing at the glacier surface. Rising mean—and especially summer—air temperatures lengthen the ablation season and intensify melt, while changes in precipitation regime (a declining fraction of solid precipitation and a shift of precipitation toward the shoulder seasons) weaken accumulation conditions. An additional driver is the modification of the surface energy balance: increased absorption of incoming shortwave radiation due to reduced albedo (dust loading, deposition of aerosol impurities, and exposure of firn-ice surfaces) accelerates glacier wastage and amplifies intra-seasonal contrasts in melt rates. Collectively, these processes manifest as a reduction in glacier area, thinning of the ice cover, fragmentation of glacier bodies, degradation of firn zones, and subsequent reorganization of glacier morphology, including upward shifts in the accumulation boundary and the retreat and shortening of glacier tongues [1, 3, 6].

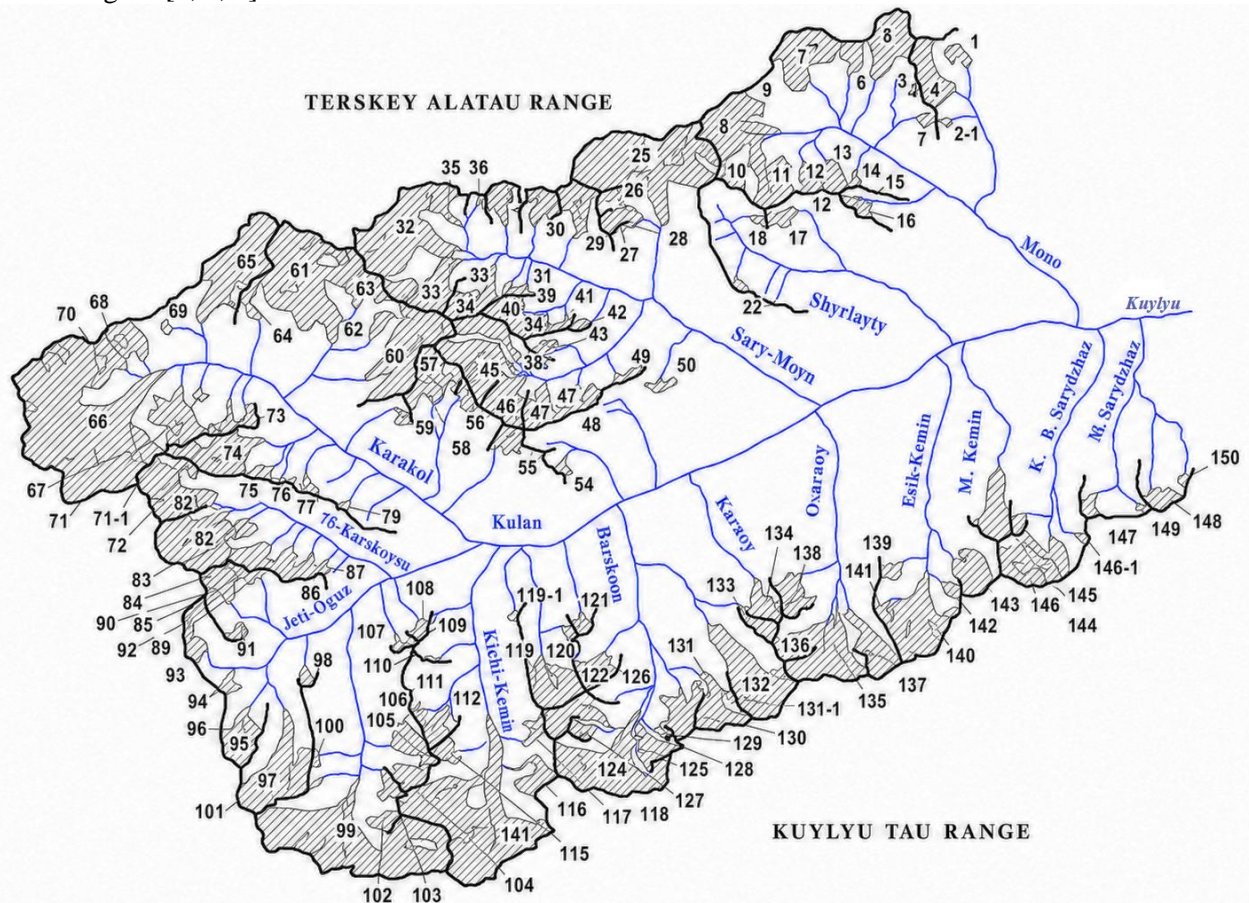


Figure 2. Map-scheme of the placement of glaciers in the Kuylyu River basin

Glacier degradation in the Tien Shan is widely regarded as one of the most evident indicators of contemporary climate change, because glaciers respond integratively to shifts in the temperature-precipitation regime and radiative conditions. The hydrological implications of these changes are of fundamental importance for mountain and piedmont basins, where glacier-snow meltwater sustains seasonal runoff stability under arid and semi-arid climates. As glacier storage declines, runoff characteristics are being altered, including reduced reliability of summer water supply, increased intra-seasonal variability of water resources, temporal shifts in peak discharge, and a growing share of short-lived flood events. In the early stages of glacier wastage, a temporary increase in runoff may occur due to accelerated melt; however, as glacier volume continues to decrease, a transition toward sustained reductions in glacier contribution and rising water-management risks becomes increasingly likely for irrigated agriculture, hydropower generation, and domestic water supply [1, 6–7]. In addition, glacier fragmentation and morphological transformation promote the formation of glacial lakes and increase the probability of hazardous processes (debris flows, glacial lake out-

burst floods, and ice-rock avalanche events), underscoring the need for strengthened basin-scale monitoring and hazard assessment [6-7].

The Western and Central Tien Shan exhibit pronounced contrasts in orographic structure, elevation belts, microclimatic conditions, and glacier types, which leads to differences both in glacier sensitivity to climatic forcing and in the nature of downstream hydrological impacts. The Western Tien Shan is typically dominated by small cirque, hanging, and cirque-hanging glaciers that form at comparatively lower absolute elevations and under higher insolation. These glaciers have restricted accumulation areas, thin ice bodies, and relatively short response times, making them highly sensitive to temperature changes and to interannual variability in winter-spring snowiness. Consequently, they tend to show rapid area loss, increasing fragmentation, and high year-to-year variability in ablation-related parameters [7-8].

In contrast, the Central Tien Shan is characterized by large valley and complex-valley glaciers with extensive accumulation zones, substantial ice reserves, and more inertial responses to climatic variability. The presence of broad firn fields and comparatively favorable accumulation conditions may partly offset increasing ablation; nevertheless, under sustained warming, a persistent upward shift of the accumulation boundary, degradation of firn zones, and accelerated thinning of glacier tongues are observed. Thus, despite their greater inertia, large valley glaciers in the Central Tien Shan display a long-term tendency toward reductions in both volume and area, which may ultimately decrease the guaranteed glacier contribution to runoff and modify water-resource regimes at the basin scale [7–10]. Taken together, the spatial heterogeneity of glacier responses across the Western and Central Tien Shan highlights the need for a differentiated monitoring strategy that combines remote sensing for assessing glacier area and morphology, glaciological observations for mass balance, and modeling approaches for projecting hydrological consequences [1, 6, 7, 9, 11].

The Western and Central Tien Shan differ markedly in orographic structure, elevation settings, climatic conditions, and glacier types. In the Western Tien Shan, small cirque, hanging, and cirque-hanging glaciers dominate; they develop at comparatively lower absolute elevations and under higher insolation. These glaciers are characterized by limited accumulation areas and high sensitivity to changes in the thermal regime. In contrast, the Central Tien Shan is largely dominated by large valley and complex-valley glaciers with extensive accumulation zones and a more inertial response to climatic variability [7–9].

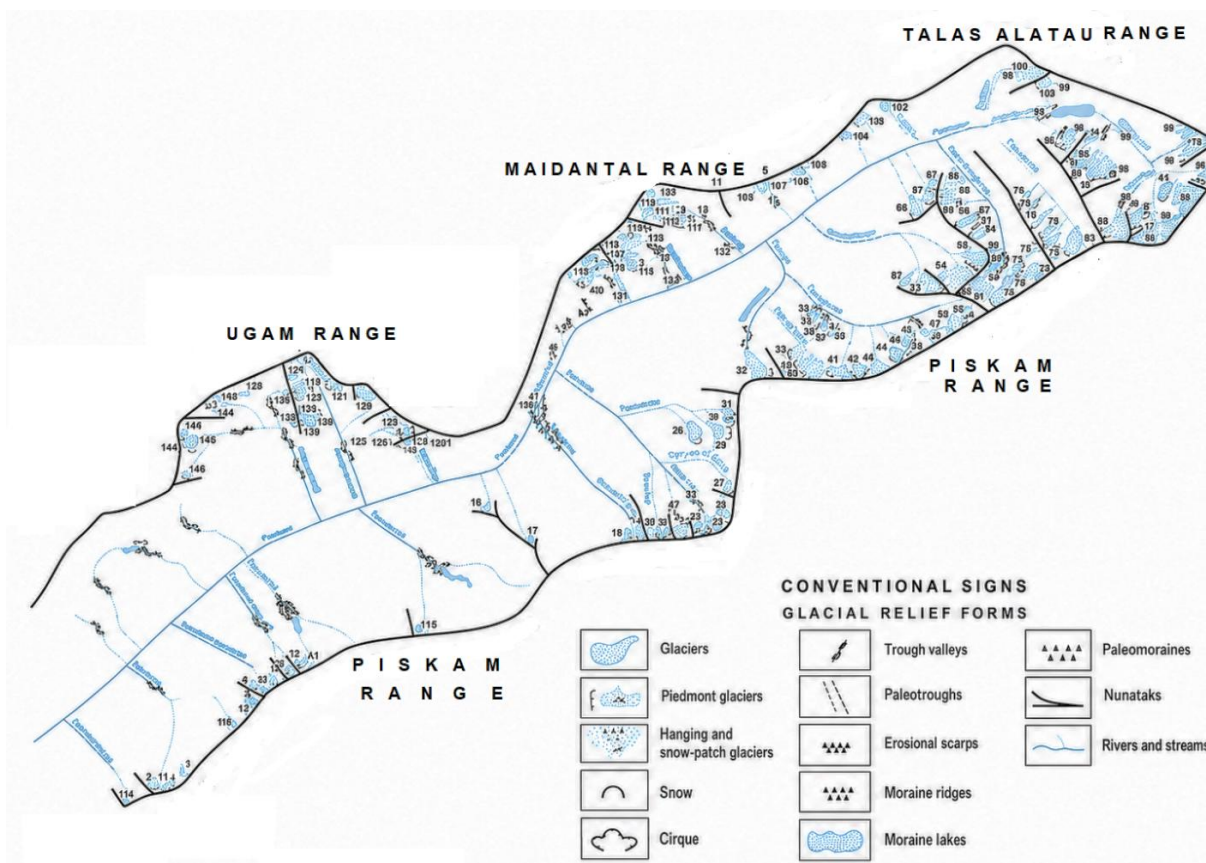


Figure 3. Map-scheme of the placement of glaciers in the Pskem River basin

Despite the substantial body of glaciological research addressing the current state and dynamics of Tien Shan glaciation, most studies typically focus on individual regions, basins, or local glacier systems. This approach provides detailed insights into site-specific patterns, yet it constrains the identification of interregional contrasts and limits the ability to generalize degradation mechanisms across the mountain system as a whole. Consequently, comparative studies that evaluate glacier degradation in the Western and Central Tien Shan from a unified methodological perspective—particularly those that harmonize glacier outline delineation criteria, ensure comparability of temporal records, and interpret changes with explicit consideration of morphological and orographic controls—remain underrepresented in the contemporary literature. This gap hampers the development of an integrated understanding of the spatial heterogeneity of degradation rates and complicates scientifically grounded projections of water-resource change in mountain regions where glacier-snow meltwater plays a critical role in sustaining seasonal runoff stability [2, 12].

Accounting for glacier morphological type and slope aspect is essential for interpreting glacier degradation. These factors strongly influence the balance between accumulation and ablation, the radiative regime, insolation intensity, wind-driven snow redistribution, and ultimately the resilience of glacier bodies to modern warming. Morphological classification (cirque, hanging, cirque-hanging, valley, and complex-valley glaciers) reflects differences in glacier geometry and internal structure, the size and elevational range of accumulation areas, and the mechanisms governing mass and heat transfer. Slope aspect, in turn, controls the receipt of solar radiation and thus the intensity of ablation and the likelihood of degradation of accumulation zones. Integrating morphological and related characteristics enables a more robust interpretation of the spatial heterogeneity of glacier change, facilitates the identification of dominant transformation mechanisms, and improves the accuracy of regional assessments.

In this study, glacier degradation in the Western and Central Tien Shan was assessed using remote sensing data and GIS-based spatial analysis: multi-temporal satellite images were harmonized to a common projection and spatial resolution, glacier outlines were delineated, and an inventory was compiled in a geodatabase with stable IDs and attributes; to minimize errors in multi-temporal matching, glacionym formation and transcription rules were standardized using a physical-geographical approach, and adjacent feature names were harmonized to ensure toponymic consistency [13-14]. For each time slice, changes in glacier area, terminus retreat, fragmentation indicators, and redistribution across elevation zones were calculated; regional trends were then compared, and the results were interpreted in relation to topographic controls and proxies of anthropogenic pressure associated with urban-rural gradients, as well as within the context of efficient water-resources management [5, 11, 15]. Outline accuracy was evaluated using confidence classes accounting for terrain shadowing, remnant snow, and debris cover, and all processing parameters were documented for reproducibility [13].

Against this background, the aim of this study is to conduct a comparative analysis of mountain glacier degradation in the Western and Central Tien Shan and to identify regional differences in the rate and character of glacier area reduction. The analysis focuses on evaluating the role of glacier morphological type and slope aspect in shaping contemporary degradation trends, and on determining the factors responsible for differences in the sensitivity of glacier systems in the two regions to ongoing climate change.

To achieve this aim, the study addresses the following objectives:

- analyze the spatio-temporal dynamics of glacier area in the Western and Central Tien Shan using comparable time slices;
- classify glaciers by morphological type and slope-aspect characteristics to establish comparable classification groups;
- quantify rates of glacier area reduction with respect to morphological and aspect-related factors and identify statistically significant differences between the regions;
- interpret the responses of glacier systems in the Western and Central Tien Shan to contemporary climatic changes and discuss potential hydrological implications in the context of regional water security.

Materials and methods

The investigation of mountain glacier degradation in the Western and Central Tien Shan was conducted within an integrated physical-geographical framework that combines glacier inventory sources, Earth observation data, and GIS-based processing of spatial information. The integration of retrospective inventory records with contemporary satellite observations ensures the comparability of results for a cross-regional assessment of glacier systems operating under contrasting orographic and climatic conditions, and reduces methodological inconsistencies arising from differences in map scales and cartographic basemaps.

The core information base consisted of the USSR Glacier Inventory, representing glacier conditions in the 1960s–1970s [9], and the Kyrgyzstan Glacier Inventory, created using satellite imagery and GIS technologies, reflecting the location of modern glaciers [8]. These sources provide harmonized information on glacier number, area, morphological type, hypsometric position, and slope aspect, enabling reconstruction of long-term glacier dynamics and the assessment of interregional differences in rates of glacier-area reduction. To ensure robust comparisons across time slices, inventory datasets were converted to a unified attribute structure, including standardization of classification variables and harmonization of morphological-type terminology.

For the Western Tien Shan, the analysis focused on the Pskem River basin as a representative region dominated by small cirque and hanging glacier forms (Fig. 4). For this basin, the study utilized results from field and office-based investigations as well as published regional studies addressing glacier dynamics and transformation under contemporary climate variability [12]. As a comparative reference and to support interpretation of regional contrasts, we also incorporated synthesis studies for the Central Tien Shan based on remote sensing and glaciological monitoring datasets, which enables the comparison of degradation trends across glacier systems differing in scale and dominant glacier types [6-7].

Contemporary changes in glacier area were quantified using Landsat and Sentinel satellite imagery, which provide long, spatially and temporally consistent observation records [6]. Image selection accounted for seasonality: priority was given to scenes acquired near the end of the ablation season, when seasonal snow cover is minimal and the “ice/rock” boundary is most distinct, thereby reducing the risk of overestimating glacier area due to snow patches and transient snow cover. Glacier outlines were delineated using spectral characteristics of ice and firn, complemented by morphological criteria (e.g., tongue geometry, nourishment type, and topographic setting). The resulting polygons were subjected to visual and cartographic verification using multi-date composites and cross-checking against topographic basemaps, which improved boundary reliability and reduced interpretation errors.

Spatial processing and analysis were performed in a GIS environment, allowing refinement not only of glacier area but also of hypsometric position, morphological type, and slope aspect. For each glacier, the following attributes were compiled: (I) area, (II) elevation range (minimum/maximum), (III) mean elevation, (IV) dominant aspect, and (V) morphological type. Aspect was derived from slope-orientation analysis within glacier outlines, enabling a quantitative assessment of the relationship between degradation rates and radiative-insolation conditions.

Glacier morphological classification followed widely accepted glaciological schemes distinguishing valley, cirque, hanging, cirque-valley, cirque-hanging, and complex-valley glaciers [3]. Applying a unified classification framework allowed the construction of comparable glacier groups for the Western and Central Tien Shan and facilitated the identification of differences in the response of distinct morphological types to contemporary climate change. This approach supports a more robust interpretation of the spatial heterogeneity of degradation and helps to isolate typology-driven mechanisms of glacier-system transformation.

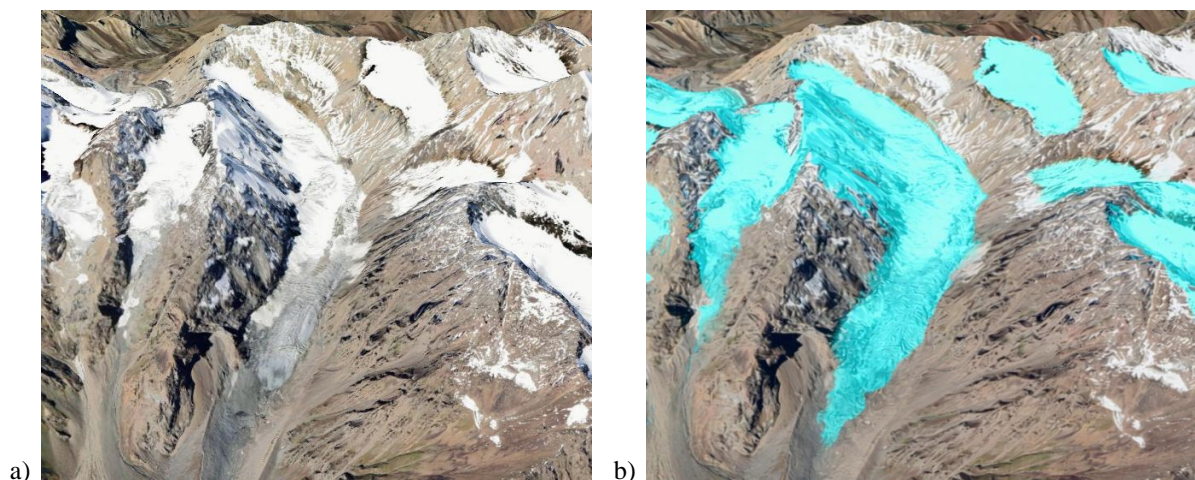


Figure 4. Space image of the Tekesh Glacier System in the Western Tian Shan (a) and the area occupied by the glacier (b)

To evaluate the impact of factors, digital elevation models (DEMs) were used to derive slope orientation and to assign glaciers to the main aspect classes [2, 6]. The aspect-based analysis enabled a shift from qualitative description to a quantitative assessment of the role of radiative-insolation conditions in shaping the spatial heterogeneity of degradation. Slope orientation was treated as a proxy for differences in incoming solar radiation, ablation-season duration, and local thermal regime, which are directly expressed in the rates of glacier area reduction. To ensure cross-regional comparability, aspects were classified using a standardized scheme (cardinal and intercardinal directions), after which area-change metrics were calculated for each aspect group.

Quantitative estimates of glacier degradation were obtained by comparing glacierized area across multiple time slices. The primary analytical metric was the temporal change in glacier area, calculated for each glacier and then aggregated by morphological type and aspect class. The results are presented in tables (Tables 1-2) that summarize glacier-area dynamics and contrasts in shrinkage rates as a function of morphological type and slope aspect. This format ensures clarity and reproducibility and allows a robust comparison of glacier degradation in the Western and Central Tien Shan while maintaining consistent grouping and interpretation criteria.

The application of an integrated methodological toolkit—combining glacier inventory analysis, remote sensing data, and GIS techniques—made it possible to identify region-specific features of glacier degradation and to establish a reliable methodological foundation for subsequent analysis and interpretation. Integrating inventory-based sources with satellite observations improved the comparability of temporal snapshots and increased the robustness of conclusions to potential limitations inherent to individual datasets (e.g., differences in cartographic basemaps, image seasonality, and mapping detail).

Statistical processing was predominantly descriptive and focused on identifying spatial patterns of glacier degradation. Within the descriptive-statistics framework, distributions and variability of area-loss indicators were summarized across morphological and aspect groups, which enabled the detection of typology-dependent differences in glacier response and the identification of glacier classes most vulnerable to contemporary warming. These summaries are treated as an analytical basis for subsequent, more detailed explanation of the observed patterns in relation to orographic and climatic controls.

Results and discussion

Glacier degradation in the Western Tien Shan by morphological type

The analysis of glacier-area dynamics in the Pskem River basin for 1968–2024 indicates a high intensity of glacier degradation and pronounced morphological differentiation of changes among glacier types (Tab. 1). Over the study period, the total glacierized area decreased from 107.0 to 85.64 km², i.e., by 21.36 km², which corresponds to an overall reduction of approximately 20 %. In terms of the mean annual rate, this is equivalent to an area loss of about 0.38 km²/year, pointing to a persistent negative trend and reflecting a substantial weakening of glacier systems in the Western Tien Shan.

This pattern is consistent with the established notion that the small cirque and hanging glaciers characteristic of the Western Tien Shan exhibit heightened sensitivity to changes in the thermal regime and insolation conditions, and it further confirms the intensification of degradation processes under contemporary warming [12]. The observed morphological heterogeneity of area reduction within the basin underscores the importance of typology-based analysis and the need to interpret the results in relation to glacier morphology and orographic setting.

Table 1

Changes in glacier area (%) in the Pskem River basin by morphological type, 1968–2024

Morphological type	Glacier area, km² (1968)	Glacier area, km² (2024)	ΔS, %
Valley glaciers	11.7	11.9	+1.7
Cirque–valley glaciers	24.4	21.4	–12.3
Cirque glaciers	34.1	23.8	–30.2
Cirque–hanging glaciers	11.4	7.55	–33.8
Hanging glaciers	1.4	1.08	–22.9
Slope cirque glaciers	8.5	5.6	–34.1

Continuation of Table 1

Morphological type	Glacier area, km ² (1968)	Glacier area, km ² (2024)	ΔS, %
Complex valley glaciers	11.3	11.74	+3.9
Hanging cirque glaciers	3.5	1.97	-43.7
Asymmetric valley glaciers	0.7	0.6	-14.3
Total	107.0	85.64	-20

The most substantial area losses over the study period were recorded for small glaciers represented by cirque, cirque-hanging, and hanging morphological types, indicating their heightened vulnerability under contemporary warming. The area of cirque glaciers decreased by 30.2 %, cirque-hanging glaciers by 33.8 %, slope cirque glaciers by 34.1 %, and hanging cirque glaciers by 43.7 %. A marked reduction was also observed for hanging glaciers (-22.9 %). This pattern is consistent with the established view that small glaciers with restricted accumulation areas, low ice thickness, and an unfavorable ratio between accumulation and ablation zones exhibit high mass-balance sensitivity to changes in air temperature and insolation conditions [1–3]. Even relatively minor climatic shifts in such systems can accelerate ablation, degrade firn zones, and subsequently fragment glacier bodies, which is expressed in rapid area shrinkage and increasing complexity of glacier-outline geometry.

Cirque-valley glaciers also show a pronounced tendency toward area reduction (-12.3 %), reflecting their transitional stability between small cirque forms and more inertial valley glaciers. This glacier type is characterized by a relatively limited accumulation area combined with an extended ablation zone, as well as strong dependence on local orographic controls (shading, avalanche nourishment, and wind-driven snow redistribution). Together, these factors increase vulnerability to contemporary climatic change and enhance within-group heterogeneity of glacier response.

A different pattern is observed for large valley and complex-valley glaciers: a slight increase in area was recorded for valley glaciers (+1.7 %) and for complex-valley glaciers (+3.9 %). However, this should not be interpreted as a real expansion of glaciation. It likely reflects redistribution of ice, changes in outline configuration (including separation and/or merging of glacier units), and methodological effects in boundary delineation related to seasonal acquisition conditions and ambiguity in distinguishing glacier ice, firn, and persistent snow patches. At the same time, large glaciers generally exhibit a more inertial response due to their greater size, higher hypsometric position of accumulation areas, and comparatively more stable mass balance, which overall confers relative resistance to short- and medium-term climatic fluctuations [6–8].

Overall, glacier degradation in the Western Tien Shan is characterized by pronounced mosaicism and typology-dependent heterogeneity. The dominant contribution to the reduction of glacierized area is made by small cirque and hanging glaciers, whereas large valley and complex-valley forms exhibit relative stability over the considered time interval. These results confirm the pivotal role of glacier morphological type in shaping regional patterns of glacier degradation and are consistent with conclusions reported in earlier glaciological studies [2, 3, 12].

Glacier degradation in the Western Tien Shan as a function of slope aspect

The analysis of glacier-area change in the Pskem River basin over 1968–2024 as a function of slope aspect revealed a clear aspect-related differentiation of degradation processes (Tab. 2) and confirmed that aspect is one of the key determinants of the spatial heterogeneity of glacier degradation in the Western Tien Shan. The results demonstrate a systematic relationship between slope orientation and the rates of glacier-area reduction, reflecting contrasts in radiative-thermal conditions and differences in ablation-season duration.

Table 2

Changes in glacier area (km²) in the Pskem River basin by slope aspect, 1968–2024

Aspect	Number of glaciers	Glacier area, 1968 (km ²)	Glacier area, 2024 (km ²)	Area change (%)
North	55	25.90	15.98	-38.30
Northeast	73	40.20	32.08	-20.20
East	16	9.41	5.60	-40.50
Southeast	21	8.53	5.03	-41.00

Continuation of Table 2

Aspect	Number of glaciers	Glacier area, 1968 (km ²)	Glacier area, 2024 (km ²)	Area change (%)
South	1	0.30	0.16	-53.90
Southwest	6	1.20	1.41	+17.50
West	6	2.30	2.43	+5.60
Northwest	41	17.90	16.67	-6.80
Total	178	105.74	79.36	-24.90

The most intense reduction in glacierized area was recorded on south-, southeast-, and east-facing slopes: glacier area decreased by 53.9 % on the southern aspect, 41.0 % on the southeast, and 40.5 % on the eastern aspect. These values are interpreted as a consequence of enhanced insolation and a higher surface radiation balance on these exposures, which promotes stronger ablation and lengthens the period with positive air temperatures. Under Western Tien Shan conditions—where a substantial share of glaciation is represented by small morphological types—such a radiative-thermal regime leads to accelerated glacier wastage and fragmentation and reduces the persistence of accumulation zones [2].

North-facing slopes also experienced a considerable decrease in glacier area (-38.3 %), indicating intensified degradation even under comparatively more favorable insolation conditions. However, relative to southern and eastern slopes, degradation rates on the northern aspect are somewhat lower, consistent with reduced incoming solar radiation, a “colder” radiative regime, and more stable thermal conditions [6-7]. Thus, aspect acts not only as the driver of maximum losses on south-facing slopes but also as a regulator of inter-aspect contrasts in degradation intensity.

The most stable conditions are observed for glaciers on northwest-facing slopes, where area loss was only 6.8 %. The minimal degradation on these slopes may be explained by the combined effects of reduced insolation, longer persistence of seasonal snow cover, and a comparatively favorable accumulation-to-ablation balance, which in some cases increases the likelihood of firn-zone preservation and stabilizes glacier outlines.

In a few cases, increases in glacier area were recorded on southwest (+17.5 %) and west (+5.6 %) aspects. These values most likely reflect the influence of a limited number of large and morphologically resilient glaciers, as well as methodological effects in multi-temporal outline delineation (e.g., image seasonality, topographic shading, and ambiguity in separating glacier ice from persistent snow patches). Accordingly, such localized “positive” changes should not be interpreted as sustained glacier growth; rather, they underscore the mosaic nature of degradation processes and the need for cautious interpretation of individual cases against the background of an overall negative trend.

In total, glacier area in the Pskem River basin decreased from 105.74 to 79.36 km², corresponding to a reduction of 24.9 %. These results confirm the controlling role of slope aspect in shaping contrasts in glacier degradation rates in the Western Tien Shan and are consistent with both regional and synthesis studies on Tien Shan glaciation [2, 6-7]. Overall, glacier degradation in the Western Tien Shan exhibits pronounced aspect-related asymmetry: the largest losses occur on south- and east-facing slopes, whereas northern—and particularly northwest-facing—exposures show relative stability. Accounting for aspect is therefore essential for robust interpretation of glacier degradation and for subsequent assessment of regional water-resource change, as aspect directly affects both the magnitude and seasonality of glacier runoff contributions and the spatial structure of basin-scale hydrological responses.

Comparative analysis of the degradation of glaciers of the Western and Central Tien Shan

A comparison of the degradation patterns of glaciers in the Western and Central Tien Shan reveals fundamental differences in the rates, characteristics, and spatial organization of glacier-area loss. These contrasts arise from the combined influence of morphological, orographic, and climatic controls, which govern the sensitivity of glacier systems to contemporary warming and shape distinct accumulation-ablation regimes and radiative-balance conditions at both slope and basin scales.

Glaciers of the Western Tien Shan are characterized by accelerated degradation rates and pronounced spatial heterogeneity in area loss. The dominant contribution to the overall reduction in glacierized area is made by small cirque, cirque-hanging, and hanging glaciers, which possess restricted accumulation zones, relatively low ice thickness, and limited “inertial” capacity in their response to climatic fluctuations. In such systems, even moderate shifts in air-temperature regime and insolation conditions can rapidly intensify abla-

tion, promote firn-zone degradation, and trigger subsequent fragmentation of glacier bodies. This process is accompanied by disruption of morphological integrity and accelerated shrinkage of glacier area. The morphological and aspect-based analyses (Figs. 5-6) confirm that degradation in the Western Tien Shan is highly mosaic, exhibiting sharp contrasts among morphological types and aspect groups, consistent with regional assessments for the Pskem River basin [6, 16].

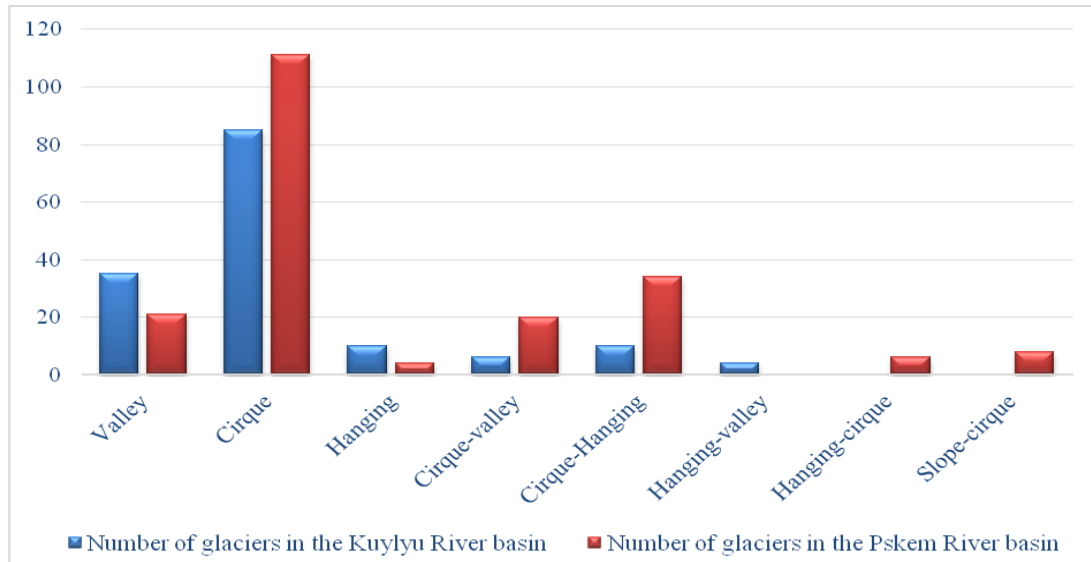


Figure 5. Comparative distribution of glacier counts by morphological type in the Kuylyu and Pskem river basins

In the Central Tien Shan, glacier degradation follows a different pathway and is generally marked by a more inertial response. Large valley and complex-valley glaciers are widespread, featuring substantial accumulation areas, high hypsometric positioning of nourishment zones, and comparatively stable conditions for firn formation and persistence. As a result, their response to contemporary climate change is expressed primarily through ice thinning and gradual frontal retreat, whereas abrupt area loss and disintegration of glacier bodies are weaker or occur only locally. This response pattern reflects both the scale-geometric properties of large glacier systems and more favorable high-altitude climatic conditions for accumulation relative to the Western Tien Shan [9, 14-15].

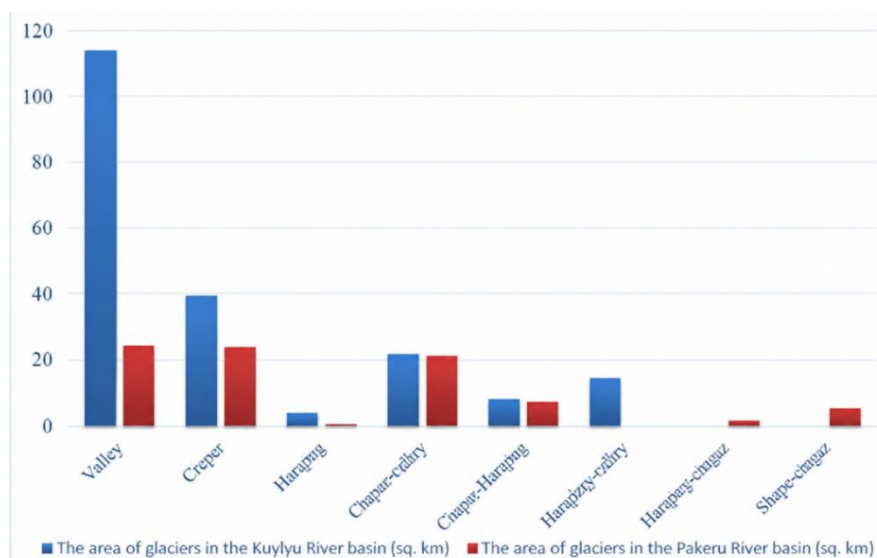


Figure 6. Comparative characteristics of glacier area by morphological type in the Kuylyu and Pskem river basins

Comparative analysis indicates that, under broadly similar regional climatic trends, rising air temperature exerts a more pronounced impact on glaciers in the Western Tien Shan than on those in the Central Tien Shan. This contrast is controlled not only by differences in the morphological structure of glaciation but also by divergent orographic and altitudinal-climatic conditions governing glacier mass balance. In particular, the hypsometric position of accumulation zones, the radiative-insolation regime, and the degree of orographic shielding—which shapes local microclimatic contrasts—play a decisive role.

In the Central Tien Shan, a substantial proportion of accumulation areas are situated at higher elevations, placing them within a thermal regime in which the influence of contemporary warming is relatively less pronounced (e.g., due to a lower frequency of above-freezing temperatures during the accumulation season and more persistent preservation of firn cover). Consequently, upward shifts of nourishment-zone boundaries and degradation of firn zones occur more gradually, and mean rates of glacier-area reduction are lower than in the western ranges, where accumulation zones are often located at lower absolute elevations and are more strongly exposed to enhanced insolation and a longer ablation season [9, 14].

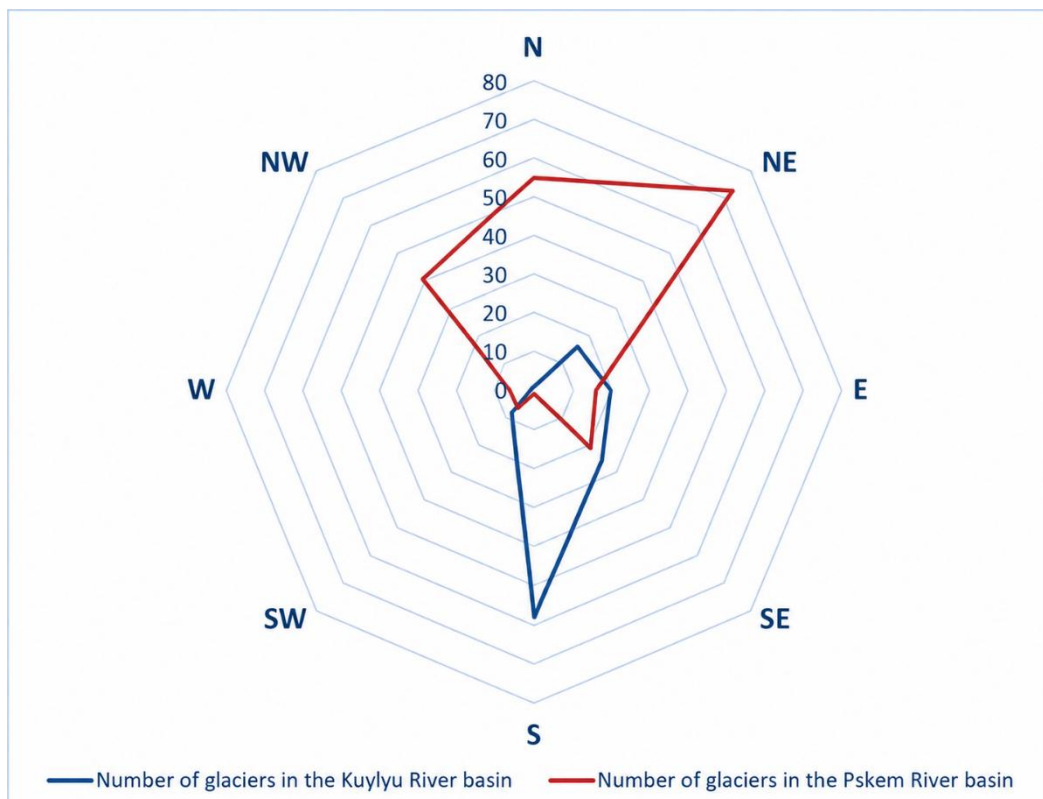


Figure 7. Comparative slope-aspect distribution of glacier counts in the Kuylyu and Pskem river basins

The aspect factor operates differently across the two regions, reflecting contrasts in glacier-system morphometry and in the radiative-thermal conditions under which glaciers function. In the Western Tien Shan, glacier degradation exhibits a distinct aspect-related asymmetry: maximum area losses are concentrated on south- and east-facing slopes, where enhanced insolation and a higher surface radiation balance intensify ablation and prolong the melt season. This dependence is especially pronounced for small cirque and hanging glaciers, which respond more rapidly and with greater contrast to changes in the surface energy regime.

In the Central Tien Shan, by contrast, the influence of aspect is less pronounced and is largely damped by the large size of valley and complex-valley glaciers, their greater inertial response, and more stable accumulation conditions associated with the high hypsometric position of nourishment zones. As a result, aspect-related contrasts in incoming solar radiation are partly compensated by glacier scale and internal stability, producing a more uniform spatial structure of degradation (Figs. 7-8) [6, 15].

Thus, the identified differences in glacier degradation between the Western and Central Tien Shan are systemic in nature and arise from the combined effects of glacier morphological type, scale-geometric properties, the hypsometric position of accumulation (nourishment) zones, and aspect-related radiative controls.

The Western Tien Shan is characterized by accelerated degradation accompanied by fragmentation of glacier bodies and a distinctly mosaic spatial pattern of area loss, whereas in the Central Tien Shan degradation generally proceeds more gradually and inertially, with dominant processes being progressive frontal retreat and ice thinning.

Accounting for these regional contrasts is essential for a robust assessment of current and projected changes in water resources in the Tien Shan mountain basins, because the type and rate of glacier degradation directly govern the seasonal reliability of runoff, intra-seasonal variability in water availability, and the level of water-management risk under ongoing climatic warming.

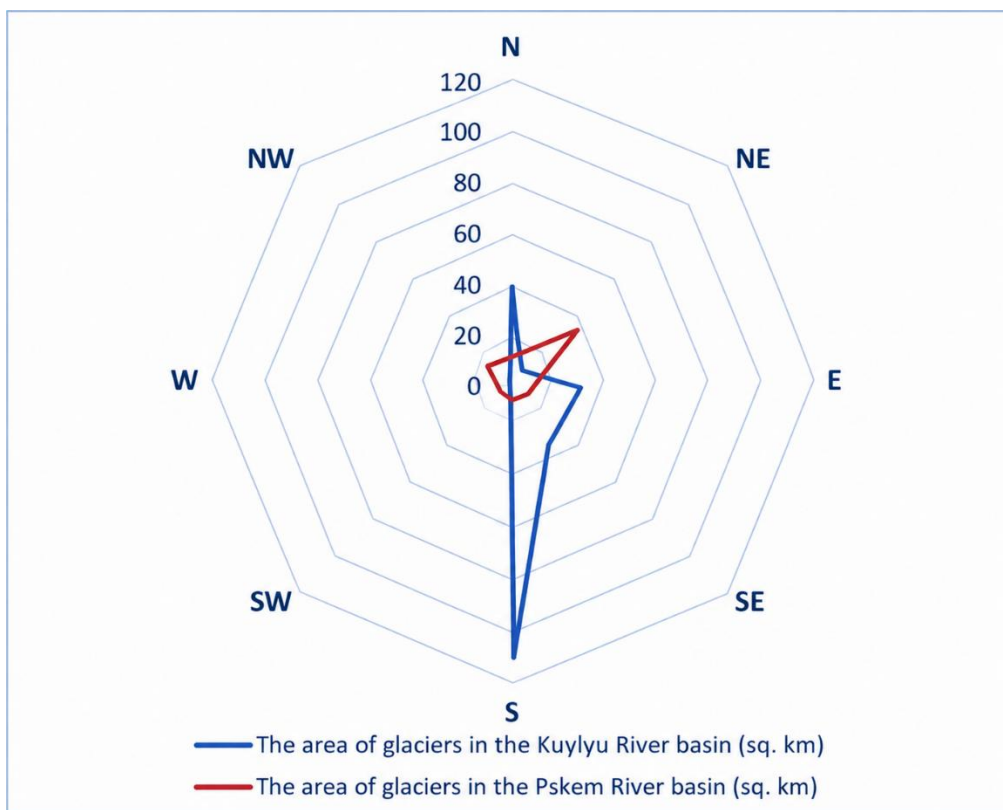


Figure 8. Comparative slope-aspect distribution of glacier area in the Kuylyu and Pskem river basins

The results confirm that glacier degradation in the Western and Central Tien Shan follows distinct trajectories despite the common forcing of contemporary climatic warming. The identified contrasts in both the rate and character of glacier-area reduction are consistent with fundamental glaciological principles that link glacier stability to morphological structure, scale-geometric properties, and orographic setting [12, 14-15]. In this context, the study demonstrates that the spatial heterogeneity of degradation is governed not only by regional climate trends but also by differences in the “internal” sensitivity of glacier systems shaped by morphological and aspect-related radiative controls.

The morphological-type analysis for the Pskem River basin indicates that the greatest area losses occur in small cirque, cirque-hanging, and hanging glaciers. Similar patterns have been reported in regional studies from the Western Tien Shan and other mountain ranges, where small glaciers are widely regarded as among the most sensitive indicators of climate change [6, 16]. Their accelerated shrinkage can be attributed to the combination of restricted accumulation areas, limited ice thickness, and strong dependence of mass balance on air temperature and the radiative-insolation regime. In such systems, even modest changes in thermal conditions and ablation-season length can rapidly intensify ablation, degrade firn zones, and trigger subsequent fragmentation of glacier bodies, which is expressed in abrupt area reduction and increasing complexity of glacier-outline geometry.

The relative stability of valley and complex-valley glaciers identified in this study is consistent with evidence for the greater inertia of large glacier systems reported for the Central Tien Shan and other high-mountain regions [9, 14-15]. Under negative mass balance, the areal response of such glaciers may occur

with a temporal lag, while the dominant modes of adjustment are ice thinning and gradual frontal retreat. This finding highlights an important methodological implication: assessments based solely on glacier area may underestimate the magnitude of change for large glaciers; therefore, the most robust approach should combine areal dynamics with changes in ice thickness/volume where such data are available.

Aspect analysis further shows that glacier degradation in the Western Tien Shan is strongly asymmetric, with maximum area losses concentrated on south- and east-facing slopes. This pattern accords with studies emphasizing the key role of insolation in shaping the spatial heterogeneity of glacier degradation [6, 15]. Greater incoming solar radiation and a longer effective ablation season on these aspects intensify melt, particularly in small morphological types characterized by short response times and high sensitivity to changes in surface energy balance. Conversely, relatively lower degradation rates on north- and northwest-facing slopes confirm the “protective” effect of reduced insolation and a more favorable thermal regime. Nevertheless, substantial area losses are observed even on these aspects, indicating that regional warming exerts a dominant influence over local orographic controls within the Western Tien Shan.

Comparison with the Central Tien Shan supports the broader conclusion that glacier-system morphology is a major determinant of regional differences in degradation. In the Central Tien Shan, the predominance of large valley glaciers with high-elevation accumulation zones reduces the sensitivity of glaciation to short-term climatic fluctuations and promotes a more inertial mode of change [9, 14]. In the Western Tien Shan, by contrast, the dominance of small glaciers enhances the mosaic spatial pattern of degradation and accelerates glacier-area loss, with direct hydrological implications.

Overall, the findings refine existing understanding of Tien Shan glacier change and underscore the need for a regionally differentiated approach to analysis and projection of glaciation trends. From an applied perspective, this is crucial for anticipating future water-resource changes: the accelerated shrinkage of small glaciers in the Western Tien Shan is potentially associated with reduced reliability of summer runoff and greater seasonal unevenness in water availability, thereby increasing water-management risks under continued warming.

Thus, the present study not only corroborates conclusions from earlier work but also extends them through a comparative assessment of the roles of morphological and aspect-related factors in glacier degradation across the Western and Central Tien Shan using a consistent methodological framework [12, 14-15]. This provides a scientific basis for further research, including the development of multifactor glacier-response models and the design of climate-adaptation scenarios for mountain regions of Central Asia.

Conclusion

The comparative analysis of mountain-glacier degradation in the Western and Central Tien Shan under contemporary climatic warming reveals fundamental regional differences in the rates, characteristics, and spatial organization of glacier-area reduction. The findings confirm that glacier change in the Tien Shan is strongly heterogeneous and emerges from the combined influence of climatic forcing, glacier morphology, and orographic controls, which jointly determine the sensitivity of glacier systems and the stability of their mass balance.

Glaciers in the Western Tien Shan exhibit a higher sensitivity to current climate change. Over 1968–2024, the total glacierized area in the Pskem River basin decreased by 20 %, with the largest losses concentrated in small cirque, cirque-hanging, and hanging glaciers. Degradation of these morphological types is accompanied by fragmentation of glacier bodies and disruption of morphological integrity, reflecting the limited inertia of small glacier systems and their rapid response to shifts in thermal and radiative regimes.

The results demonstrate that glacier morphological type is a key determinant of both the rate and mode of degradation. Large valley and complex-valley glaciers in the Western Tien Shan display relative stability under contemporary warming, which is associated with their scale-geometric properties, the high hypsometric position of accumulation zones, and comparatively more stable conditions of mass-balance formation. In contrast, small glaciers serve as the most sensitive indicators of climate variability and account for the dominant share of regional glacier-area loss.

Aspect analysis reveals a pronounced asymmetry in glacier degradation within the Western Tien Shan. Maximum area losses occur on south- and east-facing slopes, consistent with enhanced insolation and intensified ablation on these exposures. North- and northwest-facing slopes show relative stability; however, a general increase in degradation is evident even under these conditions, indicating that regional warming outweighs local orographic “protective” effects.

Comparison with the Central Tien Shan indicates a more inertial degradation pathway, expressed primarily through ice thinning and gradual frontal retreat of large valley glaciers. The greater apparent stability of Central Tien Shan glaciers is attributable to the dominance of large glacier forms, the high elevation of accumulation zones, and a more subdued influence of aspect, which reduces the contrast in the spatial response of glaciation.

These results highlight the necessity of a regionally differentiated approach to assessing Tien Shan glacier degradation and projecting associated changes in water resources. Accelerated shrinkage of small glaciers in the Western Tien Shan is potentially linked to reduced reliability of summer runoff, increased seasonal unevenness in water availability, and heightened hydrological risks in mountain and piedmont areas—underscoring the need to strengthen monitoring and to develop adaptive measures in water-resource planning.

The practical value of the study lies in the applicability of its findings for evaluating the current state of water resources, developing climate-adaptation scenarios, and planning rational water use in the mountain regions of Central Asia. The results can be used in glaciological, hydrological, and physical-geographical research and in the design of regional glacier-monitoring programs aimed at identifying the most vulnerable morphological and aspect-related glacier groups.

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М.М. Әуезов, А.А. Рисбаев

Батыс және Орталық Тянь-Шань мұздықтарының деградациясы: кеңістіктік-уақыттық трендтер мен факторлар (ЖДЗ мәліметтері бойынша)

Мақалада қазіргі климаттың жылынуы жағдайында Батыс және Орталық Тянь-Шань тау мұздықтарының деградациясына салыстырмалы талдау жасалды. Зерттеудің мақсаты морфологиялық құрылымын, экспозициялық ерекшеліктерін және орографиялық жағдайларын ескере отырып, мұздықтардың бұзылу қарқыны мен бағытының аймақтық айырмашылықтарын анықтау. Жұмыстың ақпараттық негізін КСРО мұздықтар және Қырғызстан мұздықтар каталогының материалдары, Жерді қашықтықтан зондау деректері (Landsat, Sentinel), сондай-ақ Пскем өзені бассейнінің мұздықтарын зерттеу нәтижелері құрайды. Жұмыста геоақпараттық талдау морфологиялық жіктеу және мұздану аумағының кеңістіктік-уақыттық өзгерістерін салыстырмалы бағалау әдістері қолданылды. Батыс Тянь-Шань мұздықтары климаттық өзгерістерге неғұрлым жоғары сезімталдықпен сипатталатыны және мұздық денелерінің фрагментациясымен және айқын экспозициялық дифференциациясымен жүретін деградацияның жедел қарқынын көрсететіндігі анықталды. Орталық Тянь-Шаньда деградация неғұрлым инерциялық сипатта болады және негізінен мұз жамылғысының жұқаруымен ірі аңғар мұздықтары фронттарының біртіндеп шегінуінен көрінеді. Алынған нәтижелер мұз басудың деградациясының аймақтық ерекшеліктерінің қалыптасуындағы морфологиялық және орографиялық факторлардың маңыздылығын атап көрсетеді және Орталық Азияның таулы аймақтарының су ресурстарының өзгеруін бағалауда қолданылуы мүмкін.

Кілт сөздер: мұздықтар динамикасы, мұздық жүйелері, деградация, Батыс Тянь-Шань, Орталық Тянь-Шань, климаттың өзгеруі, қашықтықтан зондау, геоақпараттық талдау, су ресурстары.

М.М. Аевзов, А.А. Рисбаев

Деградация ледников Западного и Центрального Тянь-Шаня: пространственно-временные тренды и факторы (по данным ДЗЗ)

В статье выполнен сравнительный анализ деградации горных ледников Западного и Центрального Тянь-Шаня в условиях современного климатического потепления. Цель исследования заключается в выявлении региональных различий темпов и направленности деградации ледников с учётом морфологической структуры, экспозиционных особенностей и орографических условий. Информационной основой работы послужили материалы Каталога ледников СССР, Каталога ледников Кыргызстана, данные дистанционного зондирования Земли (Landsat, Sentinel), а также результаты исследований ледников бассейна р. Пскем. В работе применены методы геоинформационного анализа, морфологической классификации и сравнительной оценки пространственно-временных изменений площади оледенения. Установлено, что ледники Западного Тянь-Шаня характеризуются более высокой чувствительностью к климатическим изменениям и демонстрируют ускоренные темпы деградации, сопровождающиеся фрагментацией ледниковых тел и выраженной экспозиционной дифференциацией. В Центральном Тянь-Шане деградация носит более инерционный характер и проявляется преимущественно в истончении ледяного покрова и постепенном отступании фронтов крупных долинных ледников. Полученные результаты подчёркивают значимость морфологических и орографических факторов в формировании региональных особенностей деградации оледенения и могут быть использованы при оценке изменений водных ресурсов горных районов Центральной Азии.

Ключевые слова: динамика ледников, ледниковые системы, деградация, Западный Тянь-Шань, Центральный Тянь-Шань, изменение климата, дистанционное зондирование, геоинформационный анализ, водные ресурсы.

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