Surface Elevation Changes of the Yinsugaiti Glacier in the Karakoram Mountains, 2000–2014: Postprint

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Abstract

Glaciers in the Karakoram region are referred to as the "Karakoram anomaly" due to their positive mass balance or surging and advancing phenomena. However, glacier changes in this region exhibit significant variations, particularly for large debris-covered glaciers, which show distinctly different responses compared to other glacier types. To understand the mechanisms of the Karakoram glacier anomaly, detailed glacier-scale change studies are essential. The Yinsugaiti Glacier, located on the northern slope of Qogir Peak in the Karakoram Mountains, is the largest glacier in China by area and a typical large debris-covered glacier. By applying differential interferometry using TanDEM-X/TerraSAR-X (February 2014) and SRTM-X DEM (February 2000), we calculated surface elevation changes of the Yinsugaiti Glacier and analyzed and discussed the glacier surface elevation changes and surging in combination with glacier surface flow velocities. The results show that from 2000 to 2014, the average surface elevation of the Yinsugaiti Glacier decreased by 1.68\$$\pm 0.94 m, indicatingoverallglacierthinning, withanannualchangerateof -$ 0.12$\pm$0.07$m \cdot a$^{-1}\$. The distribution of glacier surface elevation changes is uneven, with the southern branch (S) ice flow showing more significant overall thinning. The southern branch ice flow moves at a higher velocity, and its advancing/surging terminus occupies the glacier's main trunk, blocking the downward transport of material from the original main trunk glacier (surging), resulting in increased surface elevation of the original main trunk tongue. Glacier thinning decreases with increasing altitude initially and then stabilizes, while also exhibiting certain fluctuations. Ablation in low-elevation debris-covered areas exceeds that in bare ice zones, likely due to thinner debris cover, high thermal conductivity, and the presence of numerous supraglacial lakes and ice cliffs, which accelerate glacier ablation. In areas with slopes less than 30°, glacier thinning intensifies as slope decreases. Glaciers facing

south show slight thickness increase (0.01 m), those facing southwest show slight thinning (-0.03 m), while other aspects exhibit significant thinning. Over the past 14 years, the overall surface elevation decrease of the debris-covered Yinsugaiti Glacier indicates a state of mass loss, while glacier surging has caused local increases in glacier surface elevation.

Full Text

Preamble

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Surface Elevation Changes of Yengisogat Glacier between 2000 and 2014

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Abstract: The Karakoram glaciers are attracting increasing attention due to the 'Karakoram Anomaly' characterized by glacier surge or positive mass balance. To understand the mechanism of glacier surge or positive mass balance, a large debris-covered glacier—Yengisogat Glacier—was selected for detailed investigation. Yengisogat Glacier, the largest glacier in China, developed on the northern slope of K2 located in the Karakoram Mountains, is a dendritic glacier covering an area of 493 km^2 with four main tributaries and more than ten small glacier flows. TanDEM-X/TerraSAR-X data (acquired in Feb. 2014) and SRTM-X DEM (acquired in Feb. 2000) were employed to calculate the glacier elevation change using differential interferometry method. Similar penetration depth was assumed for the same acquired season. The glacier surface elevation change and surface velocities from published articles were integrated to discuss the mass change characteristics. The results indicated that the glacier average surface elevation was decreased by 1.68 ± 0.94 m between 2000 and 2014, which means that the glacier has lost mass by -0.12 ± 0.07 m · a ^{1}. The glacier surface elevation changes showed non-uniformity. The southern main tributary was decreased drastically. This was caused by rapid surface flow velocities which transfer the glacier mass from high altitude to low altitude ablation area. The southern main tributary occupied the original glacier trunk impeded the glacier mass transfer to low elevations which made the section elevation increased. The increased surface elevation in the tongue of glacier main trunk may be explained by glacier surge. Glacier surface elevation started to decrease along with the elevation increasing and then stayed stable, yet showing volatility at the same time. Surface elevation of thin debris-covered glacier in low altitude zones was prone to decrease than that of the exposed glacier ice. Glacier surface elevation was decreased more dramatically with the decreasing of glacier surface slope in the area where slope are less than 30 degrees. Surface elevation of glaciers with southern orientation was increased slightly while that with south-west orientation was decreased slightly, and the others were decreased drastically. The debris-covered Yengisogat Glacier experienced an overall surface elevation decline which indicated it had the mass loss although it had some local surface elevation increased due to the glacier surge.

Keywords: Yengisogat Glacier; TDX/TSX; D-InSAR; surface elevation change; glacier surge

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1 Introduction

The Karakoram glaciers have attracted widespread attention due to their anomalous behavior compared with global glacier trends, a phenomenon known as the "Karakoram Anomaly" [?, ?]. Previous studies using different digital elevation models (DEMs) have reported varying mass balance estimates. Gardelle et al. [?] used SRTM DEM data to estimate a slight mass gain of $+0.11 \pm 0.22$ m w.e. a^{1} for the Karakoram glaciers during 1999–2008. Gardner et al. [?] and Kääb et al. [?] employed ICESat GLAS data to calculate elevation changes of $-0.12 \pm 0.15\ \text{m} \cdot \text{a}^{1}$ and $-0.10 \pm 0.06\ \text{m} \cdot \text{a}^{1}$, respectively. Brun et al. [?] utilized ASTER DEM data to determine a mass balance of -0.03 ± 0.07 m w.e. a^{1} for 2000–2016. Bolch et al. [?] and Zhou et al. [?, ?] applied TanDEM-X/SRTM DEM differences to obtain mass change rates of $0.02 \pm 0.064\ \text{m} \cdot \text{a}^{1}$ and other estimates. These discrepancies highlight the complexity of glacier mass balance assessments in this region.

Yengisogat Glacier, the largest glacier in China, is located on the northern slope of K2 in the Karakoram Mountains (36.083°N, 76.1028°E) with a total area of 493 km² [?] [Figure 1: see original paper]. The glacier features four main tributaries (southwest, northwest, north, and south) and over ten smaller ice flows, extending approximately 42 km in length with elevations ranging from 4000 m to over 8000 m [Figure 1: see original paper]. The glacier surface is extensively debris-covered, particularly in the ablation zone below 4700 m.

This study employs differential interferometry using TanDEM-X/TerraSAR-X data (acquired in February 2014) and SRTM-X DEM (acquired in February 2000) to quantify surface elevation changes between 2000 and 2014. The similar acquisition seasons minimize differences in radar penetration depth. The average elevation change across the glacier was -1.68 ± 0.94 m, corresponding to a mass loss rate of $-0.12 \pm 0.07\ \mathrm{m \cdot a}^{1}$. However, the spatial pattern of elevation change exhibits significant non-uniformity [FIGURE:3 and FIGURE:4].

The TanDEM-X/TerraSAR-X system provides high-resolution X-band SAR interferometry with an 11-day repeat cycle, enabling precise topographic mapping. The differential interferometric approach assumes consistent penetration depths for the two datasets acquired in the same season. Elevation change accuracy was assessed using stable off-glacier terrain, showing a standard deviation of 2 m for the 2014–2018 period and 1.9 m for the 2014–2019 period [Figure 2: see original paper].

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4 Results and Discussion

4.1 Altitudinal Variation in Elevation Change

The elevation change patterns vary significantly with altitude. Above 4700 m, the glacier shows minimal change. Between 4500–4700 m, moderate thinning occurs. Below 4500 m, substantial surface lowering is observed, particularly in the debris-covered tongue area. The southern tributary exhibits the most dramatic thinning due to high flow velocities transferring ice mass to lower elevations. In contrast, some sections of the main trunk show surface elevation increases, potentially indicating glacier surge activity.

Surface slope significantly influences elevation change rates. On slopes less than 30°, thinning is more pronounced, with rates reaching -0.25 $\mathrm{m \cdot a}^{1}$. Between 30°–50°, thinning rates decrease, while slopes exceeding 50° show minimal change. This pattern reflects the interplay between ice dynamics and ablation processes.

The debris cover thickness also modulates elevation changes. Thin debris-covered ice experiences greater thinning than exposed ice due to enhanced melt, whereas thick debris insulates the underlying ice. The southern-oriented slopes show slight elevation gains, while southwestern slopes show slight losses, and other aspects exhibit more substantial thinning.

4.2 Glacier Velocity and Mass Transfer

Surface velocity data integrated from published studies reveal that rapid flow in the southern tributary (exceeding 200 $\mathrm{m \cdot a}^{1}$ in some sections) transports substantial ice mass from accumulation to ablation zones. This mass transfer explains the significant thinning observed in the lower reaches of this tributary. The velocity pattern suggests that the glacier trunk is currently experiencing a dynamic adjustment, with some sections thickening due to enhanced ice supply from upstream.

4.3 Implications for Glacier Mass Balance

The heterogeneous elevation change pattern indicates that Yengisogat Glacier is undergoing complex dynamic adjustments. While the overall mass balance is negative, local surface elevation increases associated with surge activity and debris cover redistribution complicate the interpretation. The results suggest that debris-covered glaciers in the Karakoram respond to climate forcing through a combination of dynamic thinning and surge-related thickening.

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5 Conclusions

This study quantifies the surface elevation changes of Yengisogat Glacier between 2000 and 2014 using TanDEM-X/TerraSAR-X and SRTM-X DEM data. The main findings are:

(1) The glacier experienced an average surface elevation decrease of 1.68 ± 0.94 m, corresponding to a mass loss rate of $-0.12 \pm 0.07\ \mathrm{m \cdot a}\ ^{1}$. The spatial pattern of elevation change is highly non-uniform, with the southern tributary showing drastic thinning while some sections of the main trunk exhibited thickening.

(2) Surface elevation changes are strongly controlled by altitude, slope, and aspect. Thinning is most pronounced at low elevations (< 4500 m) and on gentle slopes ($< 30°$). Southern-oriented slopes show slight thickening, while other aspects experience thinning. Rapid surface velocities in the southern tributary facilitate mass transfer from high to low elevations.

(3) The observed elevation increase in the glacier tongue may be attributed to glacier surge activity. Comparison with previous studies suggests that Yengisogat Glacier's mass loss rate (-0.12 $\mathrm{m \cdot a}\ ^{1}$) is consistent with regional estimates for the Karakoram, though substantial spatial heterogeneity exists. The debris-covered nature of the glacier modulates its response to climate change, with thin debris accelerating melt and thick debris providing insulation.

These results highlight the complexity of glacier response in the Karakoram region and underscore the importance of high-resolution observations for understanding the mechanisms driving the Karakoram Anomaly.

References

[1] OERLEMANS J, REICHERT B K. Relating glacier mass balance to meteoro-

logical data using a seasonal sensitivity characteristic [J]. Journal of Glaciology, 2000, 46(152): 1-6.

[2] MU Jianxin, LI Zhongqin, ZHANG Hui, et al. Mass balance variation of continental glacier and temperature glacier and their response to climate change in western China: Taking Urumqi Glacier NO.1 and Parlung NO.94 Glacier as examples [J]. Arid Land Geography, 2019, 42(1): 20-28.

[3] LIU Jie, HUANG Jinchuan, LIN Haoxi. A literature review on regionalization of water resources service function of cryosphere in China [J]. Arid Land Geography, 2018, 41(4): 751-760.

[4] HEWITT KENNETH. The Karakoram anomaly? Glacier expansion and the 'elevation effect', Karakoram Himalaya [J]. Mountain Research and Development, 2005, 25(4): 332-340.

[5] GARDELLE J, BERTHIER E, ARNAUD Y. Slight mass gain of Karakoram glaciers in the early twenty-first century [J]. Nature Geoscience, 2012, 5(5): 322-325.

[6] COPLAND L, SYLVESTRE T, BISHOP M P, et al. Expanded and recently increased glacier surging in the Karakoram [J]. Arctic, Antarctic, and Alpine Research, 2011, 43(4): 503-516.

[7] GARDNER A S, MOHOLDT G, COGLEY J G, et al. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009 [J]. Science, 2013, 340(6137): 852-857.

[8] KÄÄB A, TREICHLER D, NUTH C, et al. Brief communication: Contending estimates of 2003-2008 glacier mass balance over the Pamir-Karakoram-Himalaya [J]. The Cryosphere, 2015, 9(2): 557-564.

[9] BRUN F, BERTHIER E, PATRICK W, et al. A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016 [J]. Nature Geoscience, 2017, 10(9): 668-673.

[10] LIN H, LI G, CUO L, et al. A decreasing glacier mass balance gradient from the edge of the upper Tarim Basin to the Karakoram during 2000-2014 [J]. Scientific Reports, 2017, 7: 6712.

[11] BOLCH T, PIECZONKA T, MUKHERJEE K, et al. Brief communication: Glaciers in the Hunza catchment (Karakoram) have been nearly in balance since the 1970s [J]. The Cryosphere, 2017, 11(1): 531-539.

[12] ZHOU Y S, LI Z W, LI J, et al. Geodetic glacier mass balance (1975-1999) in the central Pamirs using the SRTM DEM and KH-9 imagery [J]. Journal of Glaciology, 2019, 65: 309-320.

[13] GARDELLE J, BERTHIER E, ARNAUD Y, et al. Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999-2011 [J]. The Cryosphere, 2013, 7(4): 1263-1286.

[14] ÖSTREM G. Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges [J]. Geografiska Annaler, 1959, 41(4): 228-230.

[15] BENN D I, BOLCH T, HANDS K, et al. Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards [J]. Earth-Science Reviews, 2012, 114(1-2): 156-174.

[16] ZHANG Y, FUJITA K, LIU S Y, et al. Distribution of debris thickness and its effect on ice melt at Hailuogou glacier, southeastern Tibetan Plateau, using in situ surveys and ASTER imagery [J]. Journal of Glaciology, 2011, 57(206): 1147-1157.

[17] QUINCEY D J, GLASSER N F, COOK S J, et al. Heterogeneity in Karakoram glacier surges [J]. Journal of Geophysical Research: Earth Surface, 2015, 120(7): 1288-1300.

[18] JIANG Z L, LIU S Y, PETERS J, et al. Analyzing Yengisogat Glacier surface velocities with ALOS PALSAR data feature tracking, Karakoram, China [J]. Environmental Earth Sciences, 2012, 67(4): 1033-1043.

[19] LIU Xingyue, JIANG Zongli, LIU Shiyin, et al. An analysis of surface velocities on Yengisogat glacier, Karakoram China [J]. Acta Geoscientica Sinica, 2018, 39(1): 103-110.

[20] ZEBKER H A, GOLDSTEIN R M. Topographic mapping from interferometric synthetic aperture radar observations [J]. Journal of Geophysical Research, 1986, 91(B5): 4993-4999.

[21] KWOK R, FAHNESTOCK M A. Ice sheet motion and topography from radar interferometry [J]. IEEE Transactions on Geoscience and Remote Sensing, 1996, 34(1): 189-200.

[22] RANKL M, BRAUN M. Glacier elevation and mass changes over the central Karakoram region estimated from TanDEM-X and SRTM/X-SAR digital elevation models [J]. Annals of Glaciology, 2016, 51(71): 273-281.

[23] RIZZOLI P, MARTONE M, GONZALEZ C, et al. Generation and performance assessment of the global TanDEM-X digital elevation model [J]. ISPRS Journal of Photogrammetry and Remote Sensing, 2017, 132: 119-139.

[24] LAMBRECHT A, MAYER C, WENDT A, et al. Elevation change of Fedchenko Glacier, Pamir Mountains, from GNSS field measurements and TanDEM-X elevation models, with a focus on the upper glacier [J]. Journal of Glaciology, 2018, 64(246): 637-648.

[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] MARSCHALK U, ROTH A, EINEDER M, et al. Comparison of DEMs derived from SRTM/X and C-Band [C]//Conference: The Shuttle Radar To-

pography Mission-Data Validation and Applications, Reston, Virginia, USA, 2005.

[27] RIZZOLI P, BRÄUTIGAM B, KRAUS T, et al. Relative height error analysis of TanDEM-X elevation data [J]. ISPRS Journal of Photogrammetry and Remote Sensing, 2012, 73: 30-38.

[28] NECKEL N, BRAUN A, KROPÁČEK J, et al. Recent mass balance of Purogangi Ice Cap, central Tibetan Plateau, by means of differential X-band SAR interferometry [J]. The Cryosphere, 2013, 7(5): 1623-1633.

[29] COPLAND L, POPE S, BISHOP M P, et al. Glacier velocities across the central Karakoram [J]. Annals of Glaciology, 2009, 50(52): 41-49.

[30] MURRAY T, STROZZI T, LUCKMAN A, et al. Is there a single surge mechanism? Contrasts in dynamics between glacier surges in Svalbard and other regions [J]. Journal of Geophysical Research, 2003, 108(B5): 2237, doi:10.1029/2002JB001906.

[31] XIE Zichu, LIU Chaohai. Introduction of Glaciology [M]. Shanghai: Shanghai Popular Science Publishing House, 2010: 490.

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