

Divergent Glacier Behaviour in the Pamir-Karakoram Region: Mass-Balance Anomalies, Surge Dynamics, and Downstream Hazard Implications

Roopjyoti Hazarika, Ujjal Deka Baruah

Abstract: *The glaciers of the Pamir and Karakoram ranges depart from the global pattern of climate-driven retreat, remaining close to balance or even gaining mass over the past two to three decades, a phenomenon widely termed the “Karakoram Anomaly.” This review synthesizes recent geodetic, remote sensing, and glaciological literature to characterize the spatial structure of this anomaly, the widespread occurrence of glacier surging in the region, and the downstream hazards posed by these dynamics. Evidence indicates that anomalous stability is concentrated in the western and central Karakoram and the Western Kunlun, while the Pamir and eastern Karakoram have recently shifted toward pronounced mass loss, consistent with a proposed west-to-east migration of the anomaly under continued regional warming. The Karakoram–Pamir region also hosts one of the two global super-clusters of surge-type glaciers, with well-documented links between surge cycles, ice-dammed lake formation, and glacial lake outburst floods (GLOFs) that threaten transboundary populations and infrastructure. This paper synthesizes published mass-balance estimates, surge inventories, and hazard assessments, and discusses implications for regional water resources and hazard management under projected future warming.*

Keywords: Karakoram Anomaly; Pamir; glacier mass balance; surge-type glaciers; glacial lake outburst flood; High Mountain Asia

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Introduction

Glaciers across High Mountain Asia (HMA) supply meltwater to some of the world's largest river systems, including the Indus, Amu Darya, and Tarim, and support the livelihoods of several hundred million people living downstream (Immerzeel, van Beek, & Bierkens, 2010). Under sustained twentieth- and twenty-first-century warming, most of these glaciers are thinning, retreating, and losing mass, mirroring the global trend of cryospheric decline (Pritchard, 2019). Within this broadly negative regional signal, however, the glaciers of the Karakoram, and to varying degrees the neighbouring Pamir and Western Kunlun ranges, have behaved anomalously: many have remained close to mass balance, some have thickened, and a large fraction exhibit episodic, dynamically driven advances known as surges (Hewitt, 2005; Gardelle, Berthier, & Arnaud, 2012; Farinotti, Immerzeel, de Kok, Quincey, & Dehecq, 2020).

This departure from the regional norm, first systematically described by Hewitt (2005) as the “Karakoram Anomaly,” has since become one of the most closely studied puzzles in contemporary glaciology. Its persistence carries direct consequences for downstream water security, for the interpretation of High Mountain Asia's contribution to sea-level rise, and because many of the anomalous glaciers are also surge-type and for hazard exposure in some of the most densely populated high-mountain valleys on Earth (Bazai et al., 2021; Farinotti et al., 2020). This paper reviews the current state of knowledge on glacier behaviour in the Pamir–Karakoram region, organized around three linked themes: (i) the spatial and temporal structure of the mass-balance anomaly and its proposed climatic drivers; (ii) the distribution and mechanics of glacier surging, which is unusually prevalent in this region; and (iii) the downstream environmental risks, principally glacial lake outburst floods (GLOFs), that arise from the interaction of surge dynamics with ice-dammed lake formation. Published geodetic mass-balance estimates, surge-glacier inventories, and hazard assessments are synthesized into comparative tables and figures, and the discussion considers the uncertainties and the likely future trajectory of glacier behaviour in the region under continued warming.

Study Area

The Karakoram range extends along the northern margin of Pakistan-administered Kashmir and into China and India, encompassing approximately 17,496 km² of glacierized area and including some of the highest peaks on Earth, among them K2

(Zhou, Sun, Xie, Zhao, Huang, Wang, & Yang, 2025). The Pamir, lying to the north-west across the Wakhan Corridor in Tajikistan, Afghanistan, and China, covers a further $\approx 12,260$ km² of glacial ice (as cited in Yao et al., 2012, and reported in subsequent regional mass-balance studies). Together with the Western Kunlun Shan, these ranges form a contiguous belt of heavily glacierized, high-relief terrain in which many glaciers descend from accumulation zones above 5,500 m to debris-covered ablation tongues at 3,000–4,000 m, producing some of the longest mid-latitude valley glaciers outside the polar regions (e.g., Baltoro, Biafo, Hispar, and Fedchenko glaciers).

A distinguishing feature of the region is the extent of supraglacial debris cover on the larger valley glaciers, which insulates the underlying ice and modifies the relationship between climate forcing and surface melt (Scherler, Bookhagen, & Strecker, 2011). Combined with the region's extreme relief and continentality, this debris mantle contributes to what Hewitt (2005) termed the “elevation effect,” in which the highest, most heavily glacierized catchments are partly buffered from the warming experienced at lower elevations

Precipitation across HMA is delivered by three principal circulation systems: the Indian Summer Monsoon, which dominates the eastern and central Himalaya; the mid-latitude westerlies, which dominate the Karakoram, Pamir, and Western Kunlun; and, more locally, winter western disturbances embedded within the westerly flow (Mölg, Maussion, & Scherer, 2014). Because the Karakoram and Pamir receive the bulk of their accumulation as winter and spring snowfall delivered by the westerlies rather than as summer monsoon precipitation, their glaciers respond to a different seasonal temperature-precipitation coupling than the summer-accumulation glaciers of the central Himalaya (Kapnick, Delworth, Ashfaq, Malyshev, & Milly, 2014). Kapnick et al. (2014) showed that Karakoram snowfall is comparatively insensitive to warming because most winter accumulation occurs at temperatures well below the rain–snow threshold, a mechanism that helps explain why Karakoram glaciers have not responded to warming in the same way as monsoon-fed Himalayan glaciers.

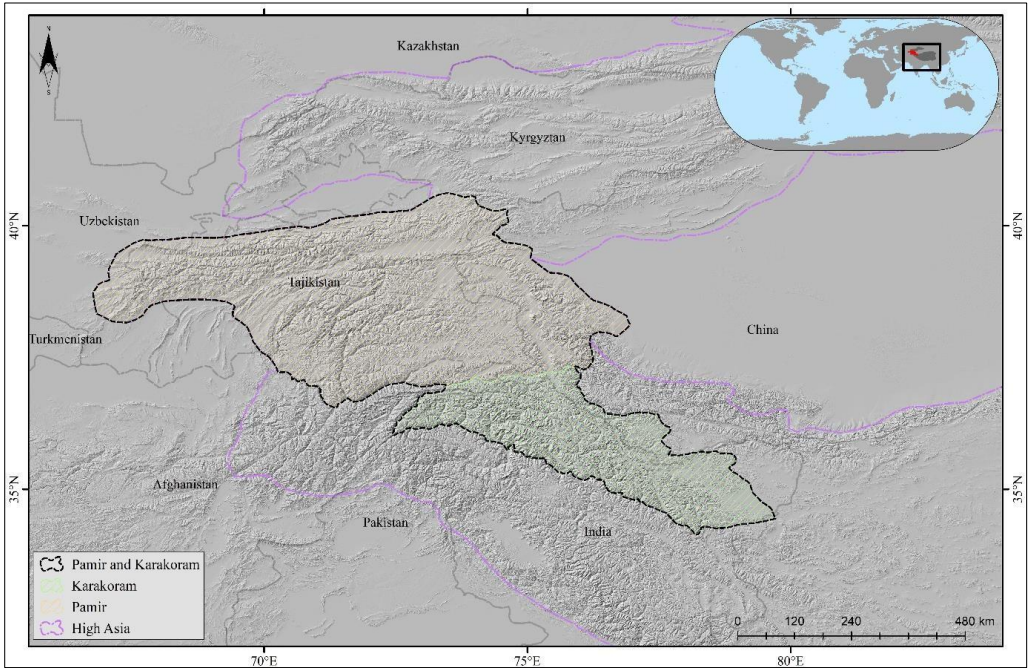


Figure 1: Location of the study area with hillshade overlay

Table 1. Physiographic and glaciological comparison of the Karakoram and Pamir ranges. Sources: Zhou et al. (2025); regional syntheses in Farinotti et al. (2020) and Azam et al. (2018)

Attribute	Karakoram	Pamir
Approx. glacierized area	17,496 km ²	12,260 km ²
Dominant moisture source	Mid-latitude westerlies; winter western disturbances	Mid-latitude westerlies, with monsoon/ENSO modulation
Accumulation season	Winter–spring (solid precipitation)	Winter–spring, extreme continental setting
Elevation range of glaciers	3,000-8,600 m (K2, 8,611 m)	3,500-7,500 m (Ismoil Somoni / Kongur peaks)
Notable characteristic	Extensive debris-covered valley glaciers; dense surge cluster	High proportion of clean-ice glaciers; second-largest surge cluster in HMA

Documented mass-balance status	Near-balance to slightly positive in west/centre; negative in east	Near-balance historically; pronounced recent loss (post-2018)
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Regional climate records corroborate a distinct thermal regime: Forsythe, Fowler, Li, Blenkinsop, and Pritchard (2017) linked Karakoram temperature and melt variability to regional atmospheric circulation rather than to hemispheric warming trends, while decadal temperature reconstructions for the eastern Pamir indicate a mean summer warming of roughly 0.7 °C since the 1950s, alongside a modest increase in annual precipitation (cited in Journal of Glaciology studies of Muztag Ata glacier mass balance). This combination of a westerlies-dominated, winter-accumulation regime and a locally buffered temperature trend forms the climatic backdrop against which the mass-balance anomaly discussed in Section 3 has developed.

The Karakoram-Pamir Mass-Balance Anomaly

3.1 Definition

The term “Karakoram Anomaly” was coined by Hewitt (2005) after field and remote-sensing observations in the 1990s revealed glacier expansion and thickening in parts of the central Karakoram, while Himalayan glaciers more broadly were retreating. Subsequent satellite geodetic studies confirmed that, since at least the 1970s, Karakoram glaciers as a whole have remained close to balance rather than following the marked negative trend recorded across most of HMA (Gardelle et al., 2012; Kääb, Berthier, Nuth, Gardelle, & Arnaud, 2012; Bolch, Pieczonka, Mukherjee, & Shea, 2017). Later work extended the anomaly geographically, showing that similar behaviour, near-zero or slightly positive mass budgets, together with widespread glacier surging, also characterizes parts of the Pamir and the Western Kunlun Shan (Gardelle, Berthier, Arnaud, & Kääb, 2013; Farinotti et al., 2020).

3.2 Spatial and Temporal Patterns

Table 2 and Figure 2 summarize a selection of published geodetic mass-balance estimates for the Karakoram and Pamir. Early region-wide assessments for 1999–2011 and the 2000s reported that the Karakoram was close to equilibrium, while adjacent Himalayan regions lost mass rapidly (Gardelle et al., 2012, 2013; Kääb, Treichler, Nuth, & Berthier, 2015). A detailed 2000–2018/19 inventory by Guillet et al. (2022), combining Shean et al. (2020) and Hugonnet et al. (2021) elevation-

change products, found median mass budgets of $-0.09 \text{ m w.e. yr}^{-1}$ for non-surge-type Karakoram glaciers and $-0.05 \text{ m w.e. yr}^{-1}$ for non-surge-type Pamir glaciers, both markedly less negative than the median losses recorded across most of HMA over the same period.

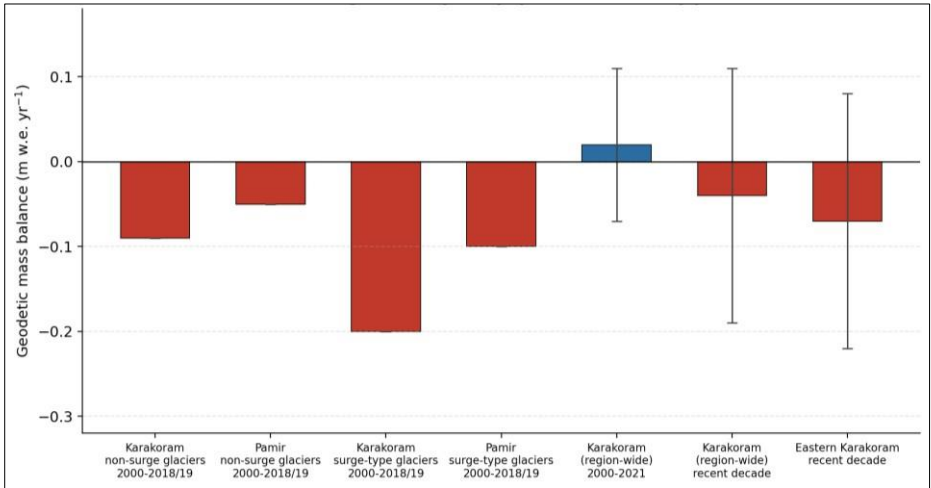


Figure 2. Published geodetic mass-balance rates for Karakoram and Pamir glaciers, by sub-population and study period. Sources: Guillet et al. (2022); Lhakpa et al. (2022); Zhou et al. (2025)

More recent work indicates that the anomaly is neither spatially uniform nor temporally stationary. Lhakpa, Fan, and Cai (2022), using SRTM and ICESat-2 data for 2000-2021, found the Karakoram as a whole essentially in balance ($+0.02 \pm 0.09 \text{ m w.e. yr}^{-1}$) but reported a clear west-east contrast: the western and central Karakoram gained ice mass while the eastern Karakoram lost mass over the same period. A subsequent assessment attributed to Zhou and colleagues (2025) found the Karakoram overall slightly negative in the most recent decade ($-0.04 \pm 0.15 \text{ m w.e. yr}^{-1}$), with losses concentrated in the eastern Karakoram ($-0.07 \pm 0.15 \text{ m w.e. yr}^{-1}$) while the anomaly persisted in the west and centre. Most strikingly, a gravimetric and altimetric reassessment covering 2003-2023 (Zhou, Sun, Abowarda, Aletoum, Huang, Lin, & Liu, 2025) found the wider Pamir-Karakoram-Western Kunlun (PKL) region losing mass overall at $-0.72 \pm 0.21 \text{ Gt yr}^{-1}$, driven primarily by substantial losses in the Pamir ($-0.90 \pm 0.09 \text{ Gt yr}^{-1}$), while the Karakoram remained close to equilibrium over the full period ($0.06 \pm 0.08 \text{ Gt yr}^{-1}$) but showed a pronounced recent deficit of $-2.23 \pm 1.52 \text{ Gt yr}^{-1}$ between 2018 and 2023; the Western Kunlun, by contrast, continued to gain mass modestly ($0.19 \pm 0.06 \text{ Gt yr}^{-1}$). These results, visualized in Figure 3, support the interpretation that the anomaly is

migrating west to east, is weakening in its original Karakoram “core” even as it persists, and has recently intensified farther west.

1.3 Driving Mechanisms

No single mechanism fully explains the anomaly, and current understanding treats it as the product of several interacting factors (Farinotti et al., 2020). The strongest and most consistently supported explanation concerns the region's distinctive precipitation regime: because Karakoram and Pamir glaciers accumulate mass predominantly from winter and spring westerly-derived snowfall rather than summer monsoon precipitation, and because this accumulation occurs at temperatures well below the melting point, these glaciers are comparatively insensitive to the same warming that drives rapid mass loss in the monsoon-influenced Himalaya (Kapnick et al., 2014; Mölg et al., 2014). Trends toward a strengthened westerly circulation and locally increased winter snowfall over parts of the twentieth and early twenty-first centuries have been proposed as a proximate driver of the positive-to-neutral mass balance observed in the western and central Karakoram (Forsythe et al., 2017).

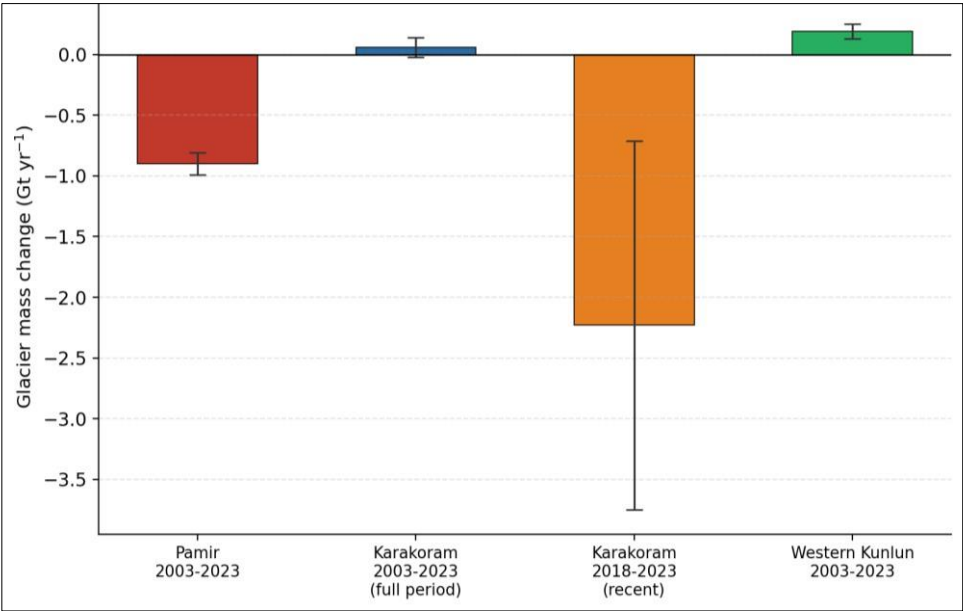


Figure 3. West-to-east migration of the Karakoram Anomaly: regional glacier mass-change rates, 2003-2023. Source: Zhou et al. (2025)

A second contributing factor is the extensive supraglacial debris cover on the region's largest valley glaciers, which insulates ablation zones and reduces melt relative to clean-ice glaciers at comparable elevations (Scherler et al., 2011).

Hewitt's (2005) “elevation effect” further notes that the Karakoram's exceptional relief concentrates a disproportionate share of glacier area at very high, cold elevations that remain buffered from lower-elevation warming. A third, more speculative mechanism concerns land-use feedbacks: de Kok, Tuinenburg, Bonekamp, and Immerzeel (2018) modelled how intensive irrigation in the arid lowlands surrounding the Karakoram may increase local atmospheric moisture and summer cloud cover, thereby suppressing incoming shortwave radiation and glacier melt. Most recently, Zhou et al. (2025) linked the persistence of the anomaly in the western and central Karakoram to increasing precipitation trends, and its breakdown in the eastern Karakoram to a locally dominant warming signal together with rising net shortwave radiation, indicating that, even within a single mountain range, different sub-catchments are currently governed by different, and diverging, climatic controls.

Table 2. Selected published geodetic mass-balance estimates for the Karakoram and Pamir. Zhou et al. (2025a) refers to “Investigating glacier mass balance and driving factors of the Karakoram Anomaly”; Zhou et al. (2025b) refers to “Has the Karakoram anomaly persisted over the past two decades?”

Region / sub-population	Period	Mass-balance rate	Source
Karakoram, non-surge-type glaciers	2000-2018/19	-0.09 m w.e. yr ⁻¹	Guillet et al. (2022)
Pamir, non-surge-type glaciers	2000-2018/19	-0.05 m w.e. yr ⁻¹	Guillet et al. (2022)
Karakoram, surge-type glaciers	2000-2018/19	-0.20 m w.e. yr ⁻¹	Guillet et al. (2022)
Pamir, surge-type glaciers	2000-2018/19	-0.10 m w.e. yr ⁻¹	Guillet et al. (2022)
Karakoram (region-wide)	2000-2021	+0.02 ± 0.09 m w.e. yr ⁻¹	Lhakpa et al. (2022)
Karakoram (region-wide)	recent decade (~2010s-2020s)	-0.04 ± 0.15 m w.e. yr ⁻¹	Zhou et al. (2025a)
Eastern Karakoram	recent decade	-0.07 ± 0.15 m w.e. yr ⁻¹	Zhou et al. (2025a)
Pamir-Karakoram-W. Kunlun (PKL) total	2003-2023	-0.72 ± 0.21 Gt yr ⁻¹	Zhou et al. (2025b)

Pamir	2003-2023	$-0.90 \pm 0.09 \text{ Gt yr}^{-1}$	Zhou et al. (2025b)
Karakoram (full period)	2003-2023	$0.06 \pm 0.08 \text{ Gt yr}^{-1}$	Zhou et al. (2025b)
Karakoram (recent)	2018-2023	$-2.23 \pm 1.52 \text{ Gt yr}^{-1}$	Zhou et al. (2025b)
Western Kunlun	2003-2023	$+0.19 \pm 0.06 \text{ Gt yr}^{-1}$	Zhou et al. (2025b)

1.4 Persistence and the West-to-East Migration of the Anomaly

Taken together, the studies summarized in Figure 2 and Figure 3 point to a coherent regional pattern: the anomaly's “centre of gravity” has shifted westward and northward relative to its original Karakoram description, with the Western Kunlun now showing the strongest and most consistent mass gains, the western and central Karakoram remaining close to balance, and the eastern Karakoram and most markedly, the Pamir shifting toward substantial mass loss (Zhou et al., 2025; Lhakpa et al., 2022). This pattern is consistent with the broader theoretical expectation articulated by Farinotti et al. (2020) that the anomaly reflects a delicate, regionally specific balance between accumulation and ablation processes that is unlikely to persist indefinitely under continued global warming. Independent modelling work using the Python Glacier Evolution Model likewise projects that the Pamir Alay, despite an almost balanced present-day budget, is likely to experience disproportionately large mass loss later this century as warming outpaces any compensating increase in precipitation (cited in HMA-wide glacier projection studies through 2100). Evidence of unusually severe glacier mass loss recorded in the Pamir during 2025, linked to anomalous atmospheric circulation and reduced snowfall, has been interpreted by recent authors as an early signal of this transition.

Surge Dynamics in the Pamir-Karakoram

4.1 Inventory and Regional Distribution

Glacier surging, a quasi-periodic oscillation between long intervals of slow “quiescent” flow and short episodes of highly accelerated “active-phase” flow, during which ice is rapidly transferred from an upper reservoir zone to a lower receiving zone, affects only around 1% of glaciers worldwide, but is heavily concentrated in two global “super-clusters”: the Arctic ring (Alaska, Arctic Canada, Svalbard, and the Russian High Arctic) and High Mountain Asia (Sevestre & Benn, 2015). Within HMA, the Karakoram and Pamir together host the overwhelming

majority of documented surge-type glaciers. Using a multi-factor remote-sensing approach combining surface elevation change, ITS_LIVE velocity data, and very-high-resolution imagery, Guillet et al. (2022) identified 666 surge-type glaciers across HMA for the period 2000-2018, of which 223 were located in the Karakoram and a further 223 in the Pamir together accounting for two-thirds of all surge-type glaciers identified in the region (Table 3, Figure 3). Earlier, more spatially limited inventories reached broadly consistent totals: Bhambri, Hewitt, Kawishwar, and Pratap (2017) documented 223 surge-related glacier phenomena across an area including the Karakoram and neighbouring Wakhan Pamir, Aghil, and Chang Chenmo mountains, comprising roughly half of the total perennial ice cover of the Karakoram; and Goerlich, Bolch, and Paul (2020) identified 206 surge-type glaciers in the Pamir from historical imagery spanning 1968-2018.

Guillet et al. (2022) further showed that surge-type glaciers account for a disproportionate share of total glacierized area in these ranges, 45.3% of RGI-mapped glacier area in the Karakoram and roughly 34-36% in the eastern and western Pamir, reflecting the fact that surge-type glaciers are systematically longer, larger, and have gentler surface slopes than their non-surging neighbours, consistent with the enthalpy-balance theory of glacier surging.

4.2 Mechanisms of Surging

Two broad mechanistic classes of surge behaviour have historically been distinguished: “Svalbard-type” surges, attributed to a thermal switch in polythermal glacier beds, and “Alaskan-type” surges, attributed to instabilities in subglacial hydrology (summarized in Guillet et al., 2022). More recent theoretical work reframes both mechanisms within a unifying enthalpy-balance framework, in which surging occurs whenever the thermal energy and water generated at a glacier bed cannot be evacuated as fast as it accumulates, producing basal instability; this theory correctly predicts that longer glaciers with gentler slopes, common in the Karakoram and Pamir, are disproportionately likely to surge. Local topographic controls also matter: Copland et al. (2011) showed that surges in several large Pamir glaciers, including Sugran and Oktyabr'sky, are strongly influenced by dynamic interactions between trunk and tributary ice streams, whereby tributary surges can trigger or propagate surging in connected drainage networks. Copland et al. (2011) further documented a marked recent increase in the incidence of glacier surging across the Karakoram, raising the possibility that changing valley and drainage-network geometry, rather than random variability, may be modulating surge frequency over time.

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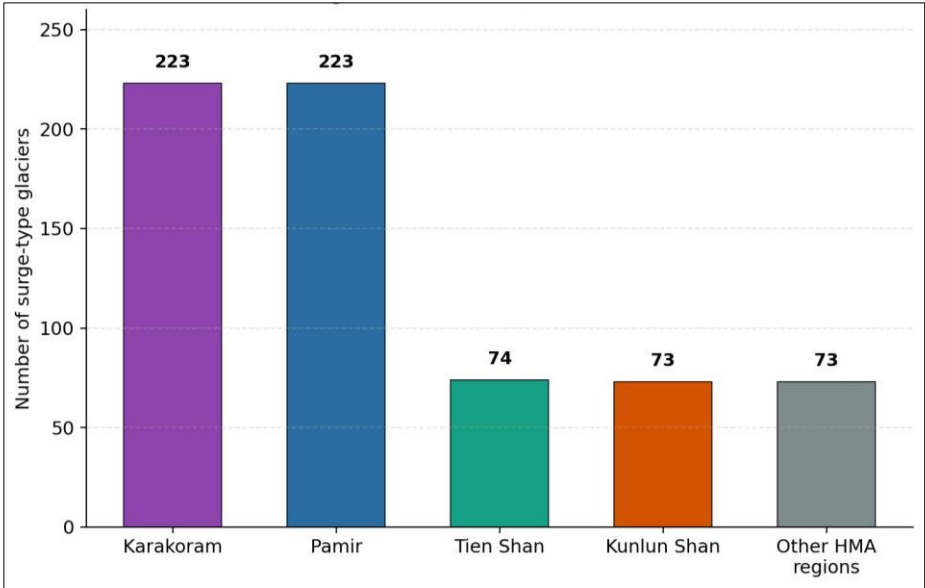


Figure 4. Regional distribution of surge-type glaciers across High Mountain Asia, 2000-2018 (n = 666). Source: Guillet et al. (2022)

Table 3. Regional distribution of surge-type glaciers in High Mountain Asia. Source: Guillet et al. (2022)

HMA region	Number of surge-type glaciers (2000–2018)	Share of regional glacier area affected
Karakoram	223	45.3%
Pamir (east + west)	223	~34-36%
Tien Shan	74	not reported
Kunlun Shan	73	not reported
Other HMA regions (Tibetan Plateau, Qilian Shan, Himalaya, Hindu Kush, etc.)	73	generally <1% per region
Total (HMA)	666	19.5% of total HMA glacierized area

1.5 Surge-Mass Balance Interactions

Because a surge redistributes ice from a high, cold reservoir zone to a lower, warmer receiving zone, it can substantially alter a glacier's local mass balance without

necessarily reflecting any change in climatic forcing. Guillet et al. (2022) found median mass budgets of surge-type glaciers markedly more negative than their non-surging neighbours across the greater HIMAP regions and close to $-0.20 \text{ m w.e. yr}^{-1}$ in the Karakoram and $-0.10 \text{ m w.e. yr}^{-1}$ in the Pamir, compared with -0.09 and $-0.05 \text{ m w.e. yr}^{-1}$, respectively, for non-surge-type glaciers (Table 2). Detailed case studies of individual surge cycles illustrate the mechanism: Khurdopin Glacier in the Hunza basin showed balanced or slightly positive mass balance during its quiescent phase and the early stages of its most recent surge (2010-2016), but experienced substantial mass loss (-0.22 to $-0.30 \text{ m w.e. yr}^{-1}$) during the later active phase and immediately following surge cessation; a similar pattern of accelerated post-surge mass loss was documented for Hispar Glacier (Guillet et al., 2022). Importantly, however, these effects appear to average out over multi-decadal timescales and do not substantially bias regional mass-balance totals unless a large number of glaciers surge repeatedly within the observation window, meaning that the anomaly documented in Section 3 is not primarily an artefact of surging, even though surging and anomalous stability co-occur extensively in this region.

Table 4. Selected notable surge-type glaciers of the Karakoram-Pamir and their associated downstream hazards. Sources: Bazai et al. (2021); Guillet et al. (2022); Mondal, Patel, Bharti, and Singh (2023)

Glacier	Location	Documented surge behaviour	Associated hazard
Khurdopin	Hunza basin, Karakoram	Recurrent surges, most recently 2015-2017 active phase	Repeated ice-dammed lake formation and GLOFs; among the most hazardous glaciers in the Karakoram
Kyagar (Kyager)	Shaksgam valley, Karakoram	Periodic surge cycles, c. 15-20 years	Together with Khurdopin, responsible for ~31.8% of major GLOFs recorded in the Karakoram
Shishper (Shisper)	Hunza basin, Karakoram	Active surge/advance 2018-2022	Ice-dammed lake breach on 7 May 2022; destroyed the Hassanabad bridge on the Karakoram Highway

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Hispar	Central Karakoram	Surge cycle including 2012-2016 active phase	Marked increase in post- surge ablation and downstream meltwater variability
Bivachny (Fedchenko Glacier complex)	Pamir, Tajikistan	Tributary surge, 2010- 2019	Locally elevated ice-mass transfer and lake-formation potential

Downstream Environmental Risk

5.1 GLOF Mechanisms and Ice-Dammed Lakes

The same surge behaviour that partially buffers regional mass balance also generates one of the region's most acute hazards. When an actively surging glacier advances rapidly across a tributary valley or the main river channel, its terminus can dam the flow of water, creating an ice-dammed lake; because the damming ice mass is itself unstable and actively deforming, these dams frequently fail, producing sudden and often repeated glacial lake outburst floods (GLOFs) (Bazai et al., 2021). Bazai, Cui, Carling, Wang, Zhang, Liu, Lei, and Zhou (2021) compiled a record of 179 GLOF events across five major Karakoram valleys spanning 1533 to 2020, and identified the Khurdopin and Kyagar glaciers as responsible for approximately 31.8% of all major GLOFs recorded in the Karakoram over that period. Using cross-correlation feature tracking, they documented surge cycles of roughly 15–20 years for the Khurdopin, Kyagar, Shishper, and Chilinji glaciers, with surge velocities in the 2010s generally exceeding those recorded in the late 1990s, a pattern consistent with an increasing, rather than static, GLOF hazard in the region.

5.2 Case Study: The 2022 Shishper Glacier GLOF

The 7 May 2022 breach of the ice-dammed lake at Shishper Glacier in the Hunza Valley of the Karakoram illustrates the compound nature of this hazard. Mondal, Patel, Bharti, and Singh (2023) used satellite remote sensing to show that Shishper Glacier's mass balance had been declining over 2017-2021, during which several smaller GLOF episodes also occurred, and that an abrupt pre-breach temperature spike drove a rapid increase in lake volume in the weeks before failure. The resulting flood destroyed the Hassanabad bridge on the Karakoram Highway, a critical transboundary transport link, and caused significant local damage, underscoring how a single surge-related GLOF can disrupt infrastructure of regional and even international importance.

5.3 Transboundary Exposure and Risk Management

The Karakoram-Pamir-Himalaya region as a whole host an extensive and, in places, transboundary population of hazardous glacial lakes. Dubey, Sattar, Gupta, Goyal, Haritashya, and Kargel (2024) identified 230 transboundary glacial lakes across the wider Hindu Kush–Karakoram–Himalaya (HKKH), of which 55 could potentially trigger cascading impacts on other glacial lakes along their flow path, five could affect more than 1,000 downstream buildings, and 35 could impact at least one hydropower facility. Regionally, comparative hazard rankings place the Pamir among the lower-hazard sub-regions of HMA relative to the eastern and central Himalaya, but the Karakoram, owing to its dense cluster of surge-type, ice-dammed-lake-forming glaciers, remains a persistent hotspot within the broader HKKH domain.

These findings collectively point to the need for sustained, basin-scale monitoring that links surge detection, lake-volume tracking, and downstream exposure assessment, particularly given that the same surge-type glaciers that stabilize regional mass balance are also the primary source of recurring GLOF hazard. Effective mitigation in this setting depends on combining remote-sensing-based early identification of surge onset with community-level early-warning systems and transboundary coordination among the states that share these river basins.

Discussion

The evidence reviewed here supports three broad conclusions. First, the Karakoram Anomaly is real, well documented across independent geodetic techniques (laser and radar altimetry, DEM differencing, and satellite gravimetry), and not merely an artefact of measurement uncertainty or of averaging over surge-type glaciers (Farinotti et al., 2020; Guillet et al., 2022). Second, the anomaly is spatially heterogeneous and, on current evidence, migrating: its strongest present-day expression lies in the Western Kunlun and western/central Karakoram, while the eastern Karakoram and, especially, the Pamir have moved toward substantial and in places accelerating mass loss over the past decade (Lhakpa et al., 2022; Zhou et al., 2025). Third, the region's unusually dense population of surge-type glaciers is mechanistically linked to, but not the primary cause of, its overall mass stability, and instead constitutes a distinct and serious hazard pathway through ice-dammed lake formation and GLOFs (Bazai et al., 2021; Guillet et al., 2022).

Several sources of uncertainty temper these conclusions. Geodetic mass-balance estimates depend on the digital elevation models, density-conversion assumptions, and the time periods used; different studies covering overlapping periods can yield somewhat different absolute values, as illustrated by the range of estimates in Table 2. Surge inventories are similarly sensitive to the detection criteria and remote-sensing datasets used, and comparisons across studies conducted over different periods and with different methods (Tables 3 and 4) should be treated as indicative rather than strictly quantitative. Field-based validation remains sparse across much of the Pamir and the more remote parts of the Karakoram, owing to the region's extreme relief and, in places, restricted access.

Looking forward, both empirical trend analysis and physically based projections suggest that the anomaly is unlikely to persist indefinitely. Farinotti et al. (2020) argue that its long-term persistence is improbable given the scale of warming anticipated under current climate projections, and glacier evolution modelling projects disproportionately large future mass loss in the Pamir Alay even under a continuation of recent, near-balanced conditions. The recent emergence of pronounced Pamir mass loss, and the weakening of the anomaly in the eastern Karakoram, are consistent with this expectation and suggest that the region may be entering a transitional phase in which the historically anomalous “core” of stability contracts further westward before eventually giving way to the retreat trend that already dominates the rest of High Mountain Asia. Given the region's role as a critical water tower and its concentration of surge-related hazard, continued high-resolution monitoring of both mass balance and surge activity will be essential for anticipating these changes and their downstream consequences.

Conclusion

The Pamir and Karakoram host one of the most distinctive glacier systems on Earth: a region where, in defiance of the global trend, many glaciers have remained close to balance and a substantial fraction advance episodically through surge cycles. This review has synthesized current evidence on the spatial structure of the resulting mass-balance anomaly, the extent and mechanics of glacier surging in the region, and the downstream hazards, principally glacial lake outburst floods, that these dynamics generate. The anomaly appears to be weakening in its historical Karakoram core and shifting toward the Pamir and Western Kunlun, a pattern with direct implications for regional water resources, for the interpretation of High Mountain Asia's contribution to global sea-level rise, and for hazard planning in

some of the most exposed transboundary mountain valleys in the world. Sustained, multi-technique monitoring combining geodetic mass-balance assessment, surge and lake-volume tracking, and downstream exposure mapping will be essential to anticipate how this globally unusual glacier system evolves under continued warming.

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References

- Azam, M. F., Wagnon, P., Berthier, E., Vincent, C., Fujita, K., & Kargel, J. S. (2018). Review of the status and mass changes of Himalayan-Karakoram glaciers. *Journal of Glaciology*, 64(243), 61–74. <https://doi.org/10.1017/jog.2017.86>
- Bazai, N. A., Cui, P., Carling, P. A., Wang, H., Zhang, G., Liu, D., Lei, Y., & Zhou, J. J. (2021). Increasing glacial lake outburst flood hazard in response to surge glaciers in the Karakoram. *Earth-Science Reviews*, 212, 103432. <https://doi.org/10.1016/j.earscirev.2020.103432>
- Bhambri, R., Hewitt, K., Kawishwar, P., & Pratap, B. (2017). Surge-type and surge-modified glaciers in the Karakoram. *Scientific Reports*, 7, 15391. <https://doi.org/10.1038/s41598-017-15473-8>
- Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., & Stoffel, M. (2012). The state

Divergent Glacier Behaviour in the Pamir-Karakoram Region: Mass-Balance
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and fate of Himalayan glaciers. *Science*, 336(6079), 310–314.
<https://doi.org/10.1126/science.1215828>

Bolch, T., Pieczonka, T., Mukherjee, K., & Shea, J. (2017). Brief communication: Glaciers in the Hunza catchment (Karakoram) have been nearly in balance since the 1970s. *The Cryosphere*, 11, 531–539. <https://doi.org/10.5194/tc-11-531-2017>

Copland, L., Sylvestre, T., Bishop, M. P., Shroder, J. F., Seong, Y. B., Owen, L. A., Windley, B., & Kamp, U. (2011). Expanded and recently increased glacier surging in the Karakoram. *Arctic, Antarctic, and Alpine Research*, 43(4), 503–516.
<https://doi.org/10.1657/1938-4246-43.4.503>

de Kok, R. J., Tuinenburg, O. A., Bonekamp, P. N. J., & Immerzeel, W. W. (2018). Irrigation as a potential driver for anomalous glacier behavior in High Mountain Asia. *Geophysical Research Letters*, 45(4), 2047–2054.
<https://doi.org/10.1002/2017GL076158>

Dubey, S., Sattar, A., Gupta, V., Goyal, M. K., Haritashya, U. K., & Kargel, J. S. (2024). Transboundary hazard and downstream impact of glacial lakes in Hindu-Kush Karakoram Himalayas. *Science of the Total Environment*, 914, 169758.
<https://doi.org/10.1016/j.scitotenv.2023.169758>

Farinotti, D., Immerzeel, W. W., de Kok, R. J., Quincey, D. J., & Dehecq, A. (2020). Manifestations and mechanisms of the Karakoram glacier Anomaly. *Nature Geoscience*, 13, 8–16. <https://doi.org/10.1038/s41561-019-0513-5>

Forsythe, N., Fowler, H. J., Li, X.-F., Blenkinsop, S., & Pritchard, D. (2017). Karakoram temperature and glacial melt driven by regional atmospheric circulation variability. *Nature Climate Change*, 7, 664–670.
<https://doi.org/10.1038/nclimate3361>

Gardelle, J., Berthier, E., & Arnaud, Y. (2012). Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature Geoscience*, 5, 322–325.
<https://doi.org/10.1038/ngeo1450>

Gardelle, J., Berthier, E., Arnaud, Y., & Kääb, A. (2013). Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011. *The Cryosphere*, 7, 1263–1286. <https://doi.org/10.5194/tc-7-1263-2013>

Goerlich, F., Bolch, T., & Paul, F. (2020). More dynamic than expected: an updated survey of surging glaciers in the Pamir. *Earth System Science Data*, 12, 3161–3176.
<https://doi.org/10.5194/essd-12-3161-2020>

Guillet, G., King, O., Lv, M., Ghuffar, S., Benn, D., Quincey, D., & Bolch, T. (2022). A regionally resolved inventory of High Mountain Asia surge-type glaciers, derived from a multi-factor remote sensing approach. *The Cryosphere*, 16, 603–623. <https://doi.org/10.5194/tc-16-603-2022>

Hewitt, K. (2005). The Karakoram anomaly? Glacier expansion and the ‘elevation effect,’ Karakoram Himalaya. *Mountain Research and Development*, 25(4), 332–340. [https://doi.org/10.1659/0276-4741\(2005\)025\[0332:TKAGEA\]2.0.CO;2](https://doi.org/10.1659/0276-4741(2005)025[0332:TKAGEA]2.0.CO;2)

Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. *Science*, 328(5984), 1382–1385. <https://doi.org/10.1126/science.1183188>

Kääb, A., Berthier, E., Nuth, C., Gardelle, J., & Arnaud, Y. (2012). Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature*, 488, 495–498. <https://doi.org/10.1038/nature11324>

Kääb, A., Treichler, D., Nuth, C., & Berthier, E. (2015). Brief communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir-Karakoram-Himalaya. *The Cryosphere*, 9, 557–564. <https://doi.org/10.5194/tc-9-557-2015>

Kapnick, S. B., Delworth, T. L., Ashfaq, M., Malyshev, S., & Milly, P. C. D. (2014). Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle. *Nature Geoscience*, 7, 834–840. <https://doi.org/10.1038/ngeo2269>

Lhakpa, D., Fan, Y., & Cai, Y. (2022). Continuous Karakoram glacier anomaly and its response to climate change during 2000–2021. *Remote Sensing*, 14(24), 6281. <https://doi.org/10.3390/rs14246281>

Mölg, T., Maussion, F., & Scherer, D. (2014). Mid-latitude westerlies as a driver of glacier variability in monsoonal High Asia. *Nature Climate Change*, 4, 68–73. <https://doi.org/10.1038/nclimate2055>

Mondal, S. K., Patel, V. D., Bharti, R., & Singh, R. P. (2023). Causes and effects of Shisper glacial lake outburst flood event in Karakoram in 2022. *Geomatics, Natural Hazards and Risk*, 14(1), 2264460. <https://doi.org/10.1080/19475705.2023.2264460>

Pritchard, H. D. (2019). Asia’s shrinking glaciers protect large populations from drought stress. *Nature*, 569, 649–654. <https://doi.org/10.1038/s41586-019-1240-1>

Scherler, D., Bookhagen, B., & Strecker, M. R. (2011). Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geoscience*, 4, 156–159. <https://doi.org/10.1038/ngeo1068>

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Anomalies, Surge Dynamics, and Downstream Hazard Implications

Sevestre, H., & Benn, D. I. (2015). Climatic and geometric controls on the global distribution of surge-type glaciers: implications for a unifying model of surging. *Journal of Glaciology*, 61(228), 646–662. <https://doi.org/10.3189/2015JoG14J136>

Zhou, S., Sun, Z., Xie, J., Zhao, F., Huang, K., Wang, H., & Yang, C. (2025a). Investigating glacier mass balance and driving factors of the Karakoram Anomaly. *ScienceDirect* (<https://www.sciencedirect.com/science/article/pii/S2214581825004410>)

Zhou, S., Sun, Z., Abowarda, A. S., Aletoum, E., Huang, Q., Lin, X., & Liu, G. (2025b). Has the Karakoram anomaly persisted over the past two decades? *GIScience & Remote Sensing*, 62(1). <https://doi.org/10.1080/15481603.2025.2548059>