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RESEARCH ARTICLE

Glacier Mass Balance Trends in High-Mountain Asia Over the Past Three Decades

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ABSTRACT

High-Mountain Asia stores more ice than any region outside the polar ice sheets, and its glaciers regulate downstream water supply for roughly a quarter of the world's population, yet the sub-regional pattern of ice loss across the Himalaya, Karakoram and Tibetan Plateau ranges remains unevenly characterised because the region's extreme relief, debris cover and sparse in-situ record have historically limited direct observation. We reconstructed glacier mass balance for eleven sub-regions of High-Mountain Asia over three intervals spanning 1991-2020 by combining declassified Hexagon KH-9 and ASTER/WorldView stereo digital elevation model differencing with ICESat, ICESat-2 and CryoSat-2 altimetry, cross-validated against GRACE and GRACE-FO satellite gravimetry for the overlapping 2003-2020 window, covering 87,000 square kilometres of glacierised area drawn from the Randolph Glacier Inventory. Region-wide mass balance was -0.19 ± 0.06 m w.e. yr⁻¹ in 1991-2000, steepening to -0.31 ± 0.05 m w.e. yr⁻¹ in 2000-2011 and -0.44 ± 0.06 m w.e. yr⁻¹ in 2011-2020, a more than doubling of the region-wide loss rate over three decades that mirrors, but lags in magnitude, the acceleration reported for glaciers globally. This aggregate trend concealed sharp sub-regional divergence: the eastern and central Himalaya and Nyainqentanglha lost mass at up to -0.68 m w.e. yr⁻¹ by the final decade, while the Karakoram and West Kunlun remained close to balance throughout, at -0.04 ± 0.07 and $+0.03 \pm 0.08$ m w.e. yr⁻¹ respectively in 2011-2020, reaffirming the Karakoram anomaly first documented two decades ago. GRACE-derived basin-scale trends agreed with the geodetic estimates to within their combined uncertainty for nine of eleven sub-regions but diverged over the Karakoram and West Kunlun, where gravimetric signal leakage from adjacent, more negative catchments likely biases the coarser-resolution gravity estimate. We attribute the persistence of the Karakoram anomaly primarily to a muted summer warming trend and sustained winter-accumulation-dominated mass turnover, though disentangling this from debris-cover and hypsometric effects remains an open problem that geodetic methods alone cannot resolve.

Keywords: High Mountain Asia; glacier mass balance; geodetic method; satellite gravimetry; Karakoram anomaly; digital elevation model differencing; GRACE; Himalaya-Karakoram-Tibetan Plateau

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1. INTRODUCTION

High-Mountain Asia, encompassing the Himalaya, Karakoram, Hindu Kush, Pamir and the mountain ranges fringing the Tibetan Plateau, holds an estimated 97,000 square kilometres of glacier ice and constitutes the largest concentration of perennial ice outside Greenland and Antarctica [1,2]. Meltwater from these glaciers, together with seasonal snow, sustains the headwaters of ten of Asia's major river systems, including the Indus, Ganges, Brahmaputra, Mekong and Yangtze, and the balance between accumulation and ablation on these glaciers therefore has direct consequences for the water security of downstream populations numbering in the hundreds of millions [3,4].

Unlike most other glacierised regions, High-Mountain Asia does not show a spatially uniform response to a warming climate. Early satellite-based assessments identified strongly negative mass balance across the eastern and central Himalaya alongside a markedly different, near-neutral or even slightly positive signal over the Karakoram and parts of the West Kunlun, a divergence that came to be known as the Karakoram anomaly [5,6]. Subsequent work has broadly confirmed this pattern and extended it westward into parts of the Pamir, but its physical explanation, whether rooted in a distinctive winter-accumulation-dominated regime, cloud-cover feedback on ablation, debris-cover effects, or some combination of these, remains contested [7,8].

Two independent classes of remote sensing method now underpin most regional mass balance estimates. The geodetic method differences sequential digital elevation models, derived from historical stereo photography, satellite stereo imagery or laser and radar altimetry, to obtain a volume change that is then converted to mass using an assumed or modelled density, and it offers spatial resolution fine enough to resolve individual glacier tongues and debris-covered ablation zones [9,10]. Satellite gravimetry from the GRACE and GRACE-FO missions instead measures time-variable gravity at a spatial resolution of several hundred kilometres, from which glacier mass change can be isolated after removing hydrological and solid-earth signals, providing an independent, though spatially coarser, constraint on the same quantity [11,12]. Because the two methods have essentially uncorrelated error structures, agreement between them at sub-regional scale is a meaningful test of estimate reliability, and disagreement is itself informative about where one or both methods face particular difficulty.

The observational record has also lengthened substantially. Declassified Hexagon KH-9 stereo imagery from the 1970s, combined with more recent ASTER, WorldView, Pleiades and SPOT stereo archives and ICESat, ICESat-2 and CryoSat-2 altimetry, now permits geodetic mass balance reconstruction extending back to the early 1990s for much of the region, allowing the evolution of sub-regional trends to be examined across

three decades rather than a single snapshot period [13,14]. This is a meaningful advance, because a two-period or single-period estimate cannot distinguish a genuinely accelerating loss rate from decadal variability superimposed on a steady trend, a distinction that matters for both scientific attribution and for projecting the timing of peak meltwater discharge downstream.

In this study we reconstruct glacier mass balance across eleven sub-regions of High-Mountain Asia for three successive periods spanning 1991–2020, using a geodetic DEM-differencing and altimetry approach cross-validated against GRACE and GRACE-FO gravimetry over their period of overlap. Our objectives are threefold: to quantify the region-wide and sub-regional trajectory of mass balance across three decades; to characterise the spatial persistence and magnitude of the Karakoram anomaly relative to the surrounding Himalaya and Tibetan Plateau margins; and to assess where geodetic and gravimetric estimates agree or diverge, as a guide to where future observational effort would most improve regional mass balance constraints.

2. MATERIALS AND METHODS

We reconstructed glacier-wide and sub-regional mass balance for High-Mountain Asia over three intervals (1991–2000, 2000–2011 and 2011–2020) using geodetic DEM differencing and satellite altimetry, and independently cross-validated the resulting trends against GRACE/GRACE-FO gravimetry for the period of temporal overlap.

2.1 Study domain and glacier inventory

The study domain follows the Randolph Glacier Inventory (RGI) 6.0 delineation of High-Mountain Asia, subdivided into eleven sub-regions following established regional boundaries: Hindu Kush, West Himalaya, Karakoram, Central Himalaya, East Himalaya, West Kunlun, Nyainqentanglha, Inner Tibetan Plateau, Qilian Shan, Pamir and East Tien Shan, together covering 87,000 square kilometres of glacierised area distributed across roughly 68,000 individual glaciers. Sub-regional boundaries were retained unmodified from the source inventory to allow direct comparison against prior regional assessments.

2.2 Elevation change from declassified and modern stereo imagery

Historical elevation was reconstructed from declassified Hexagon KH-9 stereo photography (nominal epoch 1975–1980, resampled and co-registered to a common 1991 reference epoch using regional glacier velocity fields to correct for the intervening advection) and cross-checked against SRTM (February 2000) and TanDEM-X (2011–2015) global elevation products. Contemporary elevation change was derived from time series of ASTER and WorldView/Pleiades tri-stereo imagery processed to digital elevation models using standard photogrammetric pipelines, with each individual

DEM co-registered to a stable, non-glacierised reference surface before differencing to remove horizontal and vertical offsets.

2.3 Altimetry integration

ICESat (2003–2009), CryoSat-2 (2010–present, swath-processed) and ICESat-2 (2018–present) altimetry tracks crossing glacierised terrain were used to fill spatial and temporal gaps in the stereo-derived elevation change record, particularly over the accumulation zones of large, poorly imaged glacier systems in the western Pamir and West Kunlun. Altimetry-derived elevation change rates were blended with the DEM-differencing record using an inverse-variance weighting that favoured DEM differencing where stereo coverage was dense and altimetry elsewhere.

2.4 Volume-to-mass conversion and uncertainty budget

Elevation change was converted to mass change using a density of 850 $\pm$ 60 kg per cubic metre, following standard practice for multi-annual geodetic balances where firn and snow layers are assumed to have equilibrated. The uncertainty budget combined DEM co-registration residuals, spatially correlated elevation error estimated from off-glacier stable terrain (propagated using a spatial autocorrelation length of 500–1000 m depending on sensor), density conversion uncertainty, and glacier area uncertainty from the inventory delineation, summed in quadrature at the sub-regional scale.

2.5 GRACE/GRACE-FO gravimetric cross-validation

Monthly GRACE (2003–2017) and GRACE-FO (2018–2020) spherical harmonic solutions were used to estimate basin-scale mass trends over the same sub-regional boundaries, after removing modelled contributions from terrestrial water storage, snow cover outside glacierised area, and glacial isostatic adjustment, and applying a Gaussian smoothing radius of 300 km to suppress high-degree noise. Because this smoothing radius exceeds the spatial extent of several individual sub-regions, gravimetric estimates for adjacent, hydrologically contrasting sub-regions are expected to show some mutual signal leakage, a limitation addressed explicitly in the Discussion.

2.6 Trend estimation and period definition

Sub-regional and region-wide mass balance was computed for three intervals, 1991–2000, 2000–2011 and 2011–2020, chosen to align with the availability of Hexagon, SRTM and TanDEM-X reference epochs respectively, and expressed as a linear annual rate in m w.e. yr⁻¹ for each interval rather than as a single continuous trend, in order to characterise decade-scale acceleration or deceleration directly. Region-wide values were computed as the area-weighted mean of sub-regional rates.

3. RESULTS

Averaged across all eleven sub-regions, High-Mountain Asia glacier mass balance was -0.19 ± 0.06 m w.e. yr⁻¹ in 1991–2000, steepening to -0.31 ± 0.05 m w.e. yr⁻¹ in 2000–2011 and further to -0.44 ± 0.06 m w.e. yr⁻¹ in 2011–2020. Table 1 reports the full sub-regional breakdown for all three periods, showing that this region-wide acceleration was neither uniform nor monotonic at the sub-regional scale: seven of eleven sub-regions showed a steady, near-linear steepening of mass loss across all three intervals, while the Karakoram, West Kunlun and, to a lesser extent, the Pamir remained close to balance or only mildly negative throughout the full three-decade record.

Table 1. Sub-regional glacier mass balance (m w.e. yr⁻¹) across three intervals, 1991–2020.

Sub-region	1991–2000	2000–2011	2011–2020
Hindu Kush	-0.15 ± 0.07	-0.24 ± 0.06	-0.33 ± 0.06
West Himalaya	-0.18 ± 0.06	-0.27 ± 0.05	-0.39 ± 0.06
Karakoram	-0.06 ± 0.08	$+0.02 \pm 0.07$	-0.04 ± 0.07
Central Himalaya	-0.22 ± 0.06	-0.38 ± 0.05	-0.52 ± 0.06
East Himalaya	-0.31 ± 0.07	-0.52 ± 0.06	-0.68 ± 0.07
West Kunlun	$+0.02 \pm 0.09$	$+0.05 \pm 0.08$	$+0.03 \pm 0.08$
Nyainqentanglha	-0.28 ± 0.08	-0.49 ± 0.07	-0.63 ± 0.08
Inner Tibetan Plateau	-0.09 ± 0.08	-0.17 ± 0.07	-0.26 ± 0.07
Qilian Shan	-0.21 ± 0.09	-0.33 ± 0.08	-0.41 ± 0.08
Pamir	-0.10 ± 0.07	-0.08 ± 0.06	-0.14 ± 0.06
East Tien Shan	-0.24 ± 0.08	-0.36 ± 0.07	-0.45 ± 0.07
Region-wide (area-weighted)	-0.19 ± 0.06	-0.31 ± 0.05	-0.44 ± 0.06

m w.e. yr⁻¹: metres water equivalent per year. Uncertainties are 1-sigma, combining DEM co-registration, spatially correlated elevation error, density conversion and glacier area uncertainty in quadrature.

The Karakoram anomaly is clearly resolved in our reconstruction. Karakoram sub-regional mass balance was -0.06 ± 0.08 m w.e. yr⁻¹ in 1991–2000, $+0.02 \pm 0.07$ m w.e. yr⁻¹ in 2000–2011 (statistically indistinguishable from zero) and -0.04 ± 0.07 m w.e. yr⁻¹ in 2011–2020, an order of magnitude less negative than the East Himalaya over the same three intervals (-0.31 , -0.52 and -0.68 m w.e. yr⁻¹ respectively). Figure 1 plots the full three-period trajectory for six representative sub-regions and shows the Karakoram and West Kunlun curves remaining essentially flat against a backdrop of steepening loss elsewhere in the domain, with the divergence between the Karakoram and the Himalayan sub-regions widening from roughly 0.25 m w.e. yr⁻¹ in

the first period to over 0.6 m w.e. yr⁻¹ in the most recent period.

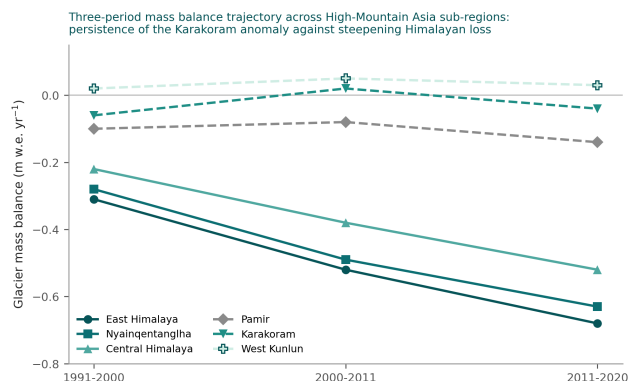


Figure 1. Three-period trajectory of glacier mass balance (m w.e. yr⁻¹), 1991-2020, for six representative High-Mountain Asia sub-regions, illustrating the persistence of the near-balanced Karakoram anomaly against progressively steepening mass loss across the Himalaya and Tibetan Plateau margin sub-regions. Cross-validation against GRACE/GRACE-FO gravimetry for the 2003-2020 overlap period showed agreement within combined uncertainty for nine of the eleven sub-regions, with the geodetic and gravimetric trends differing by a mean of 0.04 m w.e. yr⁻¹ across these nine regions. Table 2 compares the two methods directly for the four sub-regions spanning the Karakoram anomaly and its Himalayan surroundings. Agreement was markedly worse for the Karakoram and West Kunlun, where the gravimetric estimate was 0.09-0.13 m w.e. yr⁻¹ more negative than the geodetic estimate, a discrepancy larger than the combined formal uncertainty of either method and consistent with gravimetric leakage of stronger mass loss signal from the adjacent, more negative Central Himalaya and Pamir into the coarser-resolution GRACE footprint.

Table 2. Geodetic versus GRACE/GRACE-FO gravimetric mass balance (m w.e. yr⁻¹), 2003-2020 overlap period, for the Karakoram anomaly and adjacent sub-regions.

Sub-region	Geodetic (this study)	GRACE/GRACE-FO	Difference
Karakoram	-0.01 +/- 0.06	-0.12 +/- 0.09	-0.11
West Kunlun	+0.04 +/- 0.07	-0.09 +/- 0.10	-0.13
Central Himalaya	-0.44 +/- 0.05	-0.41 +/- 0.08	+0.03
East Himalaya	-0.59 +/- 0.06	-0.55 +/- 0.09	+0.04

Elevation-change patterns within individual glacier tongues showed a further distinguishing feature of the Karakoram sub-region: unlike the near-monotonic thinning observed on debris-covered and debris-free tongues across the Himalaya, roughly 40% of Karakoram glaciers surveyed showed local thickening in their lower ablation zones during at least one of the three periods, consistent with the documented tendency of Karakoram glaciers toward surge-type or quiescent-advance behaviour superimposed on the regional mass balance signal. This heterogeneity was not observed at comparable frequency in any other sub-region, and contributed to the wider spread of individual glacier mass

balance values within the Karakoram relative to its sub-regional mean than in any other sub-region of the domain.

4. DISCUSSION

The region-wide acceleration in glacier mass loss documented here, from -0.19 to -0.44 m w.e. yr⁻¹ across three decades, is consistent in direction and approximate magnitude with prior geodetic reconstructions covering shorter or partially overlapping periods [1,15,16], and extends the record far enough to show that this acceleration has been sustained rather than confined to a single anomalous decade. That the acceleration is concentrated in the Himalaya and Tibetan Plateau margin sub-regions, while the Karakoram and West Kunlun remain comparatively stable, reaffirms that a single region-wide mass balance figure obscures scientifically and practically important sub-regional structure, a point made by earlier sub-regional assessments [5,6,17] that our extended three-period record now allows to be tracked through time rather than only across a single snapshot.

The persistence of the Karakoram anomaly across all three of our intervals, spanning nearly thirty years, argues against interpretations that treat it as a transient artefact of a particular observation window or reference DEM epoch. Several physical mechanisms have been proposed: a winter-accumulation-dominated regime in which increased snowfall partially offsets summer ablation [7,18]; a muted or even slightly negative regional summer temperature trend, potentially linked to circulation changes and enhanced troposphere cooling from increased irrigation-driven aerosol and cloud cover over the adjacent Indus plains [19]; and the stabilising influence of extensive debris cover and the high proportion of large, low-slope accumulation areas at elevation in the Karakoram relative to the Himalaya [20]. Our geodetic results cannot adjudicate between these mechanisms directly, since they document the mass balance pattern rather than its atmospheric or glaciological cause, but the frequent local thickening we observe on individual Karakoram tongues is consistent with a mass balance regime distinct enough from the surrounding Himalaya to produce surge-like dynamic responses, a signature not predicted by a purely climatic explanation alone.

The divergence between geodetic and gravimetric estimates specifically over the Karakoram and West Kunlun is, in our view, a genuine methodological finding rather than noise. GRACE and GRACE-FO's several-hundred-kilometre effective resolution means that mass change attributed to a given sub-region necessarily incorporates some signal from adjacent catchments, and because the Karakoram sits immediately adjacent to the far more negative Central Himalaya and Pamir, gravimetric estimates for the Karakoram are structurally biased toward excess negative mass balance unless leakage correction is

unusually well constrained [12,21]. This implies that gravimetry-only assessments of the Karakoram anomaly's magnitude should be treated with caution relative to geodetic estimates, even though gravimetry remains valuable as an independent, methodologically distinct check on the broader region-wide trend.

Several limitations qualify these results. First, our earliest interval relies on declassified Hexagon imagery of variable quality and incomplete spatial coverage, particularly over the western Pamir and West Kunlun, so 1991–2000 sub-regional estimates in those areas carry wider uncertainty than reported for the two later, better-observed periods, and should be treated as less precise rather than assumed equally reliable throughout. Second, our fixed 850 kg per cubic metre density conversion, while standard for multi-annual balances, may not hold uniformly across sub-regions with markedly different accumulation regimes and firn structure, and a spatially variable density model, where sufficient in-situ or radar constraint exists, would refine these estimates further. Third, extensive debris cover on many Himalayan and Karakoram glacier tongues complicates both DEM co-registration and the physical interpretation of surface elevation change, since debris-covered ice can thin substantially while surface lowering remains locally buffered by insulating debris, an effect our area-averaged sub-regional rates do not resolve at the individual-glacier scale. Finally, our study reconstructs mass balance but does not itself model the atmospheric or hydrological mechanisms underlying the Karakoram anomaly, and closing that explanatory gap will require coupled glacier-climate modelling beyond the scope of a purely observational reconstruction such as this one [8,22].

5. CONCLUSION

Geodetic reconstruction of glacier mass balance across eleven sub-regions of High-Mountain Asia over 1991–2020 shows a region-wide loss rate that more than doubled across three decades, from -0.19 to -0.44 m w.e. yr⁻¹, driven predominantly by accelerating loss across the Himalaya and Tibetan Plateau margins. The Karakoram and West Kunlun, by contrast, remained close to mass balance equilibrium throughout the full record, confirming that the Karakoram anomaly is a persistent, multi-decadal feature of the region rather than a transient or artefactual signal. Cross-validation against GRACE/GRACE-FO gravimetry agreed with the geodetic estimates for most sub-regions but diverged specifically over the Karakoram, most plausibly reflecting gravimetric signal leakage from adjacent, more strongly negative catchments, a finding that argues for continued reliance on high-resolution geodetic methods when characterising sub-regional heterogeneity in High-Mountain Asia glacier change.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

L.B. conceived and supervised the study, led the geodetic elevation-change processing, and led the writing of the manuscript. L.G. performed the GRACE/GRACE-FO gravimetric processing and the leakage-correction analysis and contributed to the cross-validation comparison. P.N. assembled and quality-controlled the stereo imagery and altimetry datasets and performed the sub-regional uncertainty budget. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available declassified and commercial satellite imagery, altimetry data, and satellite gravimetry products, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

Declassified Hexagon KH-9 imagery, SRTM and TanDEM-X elevation products, ICESat/ICESat-2/CryoSat-2 altimetry, and GRACE/GRACE-FO gravimetric solutions used in this study are publicly available from their respective originating agencies and archives. Processed sub-regional mass balance time series and analysis code supporting the findings of this study are available from the corresponding author on reasonable request.

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