

Correcting Two Processing Pitfalls in Landsat Glacier Change Detection: Bualtar Glacier and the Karakoram Anomaly, 1990-2025

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1 **Correcting Two Processing Pitfalls in Landsat Glacier Change Detection:**
2 **Bualtar Glacier and the Karakoram Anomaly, 1990-2025**

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Abstract

Evidence for the Karakoram Anomaly, the stability or mass gain of Karakoram glaciers during widespread global retreat, comes mostly from region-wide averages, in which surge-type glaciers are hard to interpret. Two steps in the standard processing chain also bias such records, and the bias does not show in the output. This study addresses these gaps at Bualtar Glacier, a surge-type glacier in Hopar Valley, Nagar District, Gilgit-Baltistan, Pakistan, across eight epochs from 1990 to 2025 built from Landsat 5, 7, 8 and 9 Collection 2 products in Google Earth Engine. The conventional change-detection formulation returns one value for terrain that held ice throughout and terrain that never held ice. For 1990-1995 this inflates the reported stable class from 74.1 % to 92.5 %. Measured extent follows Landsat scene availability unless every epoch is restricted to pixels observed in all epochs. Without that restriction the chain returned roughly 20 km² of ice for 1990 and 47 km² for 2000. Six parameters were then derived on the corrected 37.08 km² common footprint. Mean glacier-surface temperature rose 1.88 °C per decade ($r^2 = 0.76$, $p = 0.005$), the only significant glaciological trend at this sample size. Ice extent declined 7.3 %, supraglacial debris expanded from 24.8 % to 29.8 %, and the interval loss rate reached 1.48 % per year during 2020-2025. The record reproduces Karakoram stability for 1990-2015 and departs from it thereafter. Both corrections are simple to apply and are relevant to any multi-decadal Landsat record of glacier change.

Keywords Karakoram Anomaly · Bualtar Glacier · Landsat Collection 2 · Land surface temperature · Supraglacial debris · Google Earth Engine

Introduction

Glaciers across High Mountain Asia have lost mass over recent decades (Bolch et al. 2012; Brun et al. 2017; Hugonnet et al. 2021). The Karakoram, for the most part, has not. Since Hewitt (2005) set out the case in detail, a large literature has recorded Karakoram glaciers holding steady, advancing, or gaining mass while the Himalaya, Hindu Kush and Tien Shan lost it (Farinotti et al. 2020; Gardelle et al. 2012). Four explanations circulate for this “Karakoram Anomaly”: heavier winter precipitation (Archer and Fowler 2004), depressed summer temperatures tied to a regional circulation peculiar to the range (Forsythe et al. 2017; Fowler and Archer 2006), the insulating blanket of thick supraglacial debris (Herreid and

Pellicciotti 2020; Scherler et al. 2011), and the exceptional concentration of surge-type ice the range carries (Bhambri et al. 2017; Copland et al. 2011).

Three gaps fall out of that literature. The first is one of scale. Geodetic records show the anomaly persisting to 2016 in the central Karakoram (Berthier and Brun 2019) and region-wide to 2021 (Lhakpa et al. 2022), but they average over thousands of glaciers, and a region-wide mean can hide individual glaciers that diverge from it. The second concerns surge-type glaciers. A surge advance followed by post-surge stagnation moves ice for reasons that have nothing to do with climate (Bhambri et al. 2017; Quincey et al. 2011), yet the basins of surge-type and surge-modified glaciers cover about 43 % of the Karakoram glacierised area (Bhambri et al. 2017), so they cannot simply be left out. The third gap is in the processing itself. Coverage is often not reported alongside glacier-change results, and change maps seldom state whether their stable class contains ice at all, so a reader cannot tell how much of a reported change comes from the processing.

All three gaps meet at Bualtar Glacier. Its surge behaviour is already in the published record (Gardner and Hewitt 1990). Its extent differs markedly between the 1997 and 2007 inventories of the Global Land Ice Measurements from Space (GLIMS) database, and the glacier is large enough that what happens on it is not local noise. Basin-scale Landsat studies have tracked glacier area across the Hunza basin, of which the Hopar valley is part (Qureshi et al. 2017). The only valley-scale satellite assessment that we found (Hussain et al. 2025) mapped snow and glacier extent from four single late-summer Landsat scenes between 1993 and 2023, as part of a study of the debris flows of August 2022. To our knowledge, no multi-decadal, multi-parameter satellite record of Bualtar Glacier itself has been published. The present record differs in using eight epochs of median composites rather than single scenes, and in measuring six parameters on one common pixel footprint. This study pursues four specific objectives: (i) to quantify how much two standard choices in the processing chain change the result, and to set out corrections for both; (ii) to quantify change in six surface parameters at Bualtar Glacier across eight epochs from 1990 to 2025, on a footprint that is comparable between epochs; (iii) to separate change attributable to post-surge dynamic readjustment from change consistent with a climate signal; and (iv) to test whether the several parameters, derived from different spectral bands and largely independent of one another, agree.

The first objective was not planned at the outset. It emerged during the work, when two errors in the conventional processing chain were found to produce results that look plausible and are wrong by large margins. One lies in how change classes are coded. The other lies in how uneven satellite coverage is handled. Both are documented in Materials and methods and quantified in the Discussion, and both are likely to affect other studies that use the same standard formulations.

Materials and methods

Study area

Bualtar Glacier (GLIMS and Randolph Glacier Inventory, RGI, identifier G074775E36208N) lies in Hopar Valley, Nagar District, Gilgit-Baltistan, Pakistan, in the central Karakoram. The analysis boundary covers 65.11 km² as a vector outline, or 64.56 km² once rasterised to the 30 m Landsat grid. It spans 2300 m to 7246 m above sea level. Mean elevation is 4741 m, median 4768 m. Mean surface slope is 25.5°; the maximum is 77.9° (Fig. 1).

Aspect is strongly asymmetric here. This is a shaded glacier. The aspects that receive least direct solar radiation carry most of its ice, and that bears directly on its survival.

Bualtar is a surge-type glacier (Bhambri et al. 2017; Copland et al. 2011; Gardner and Hewitt 1990). The inventory record shows it. The GLIMS outline dated 10 August 1997 and the outline dated 16 September 2007 do not coincide: 15.99 km² lies in the 1997 outline alone, 1.49 km² in the 2007 outline alone, 47.64 km² in both. That 15.99 km² is 24.6 % of the total boundary, and it is ice that had advanced by 1997 and retreated again by 2007.

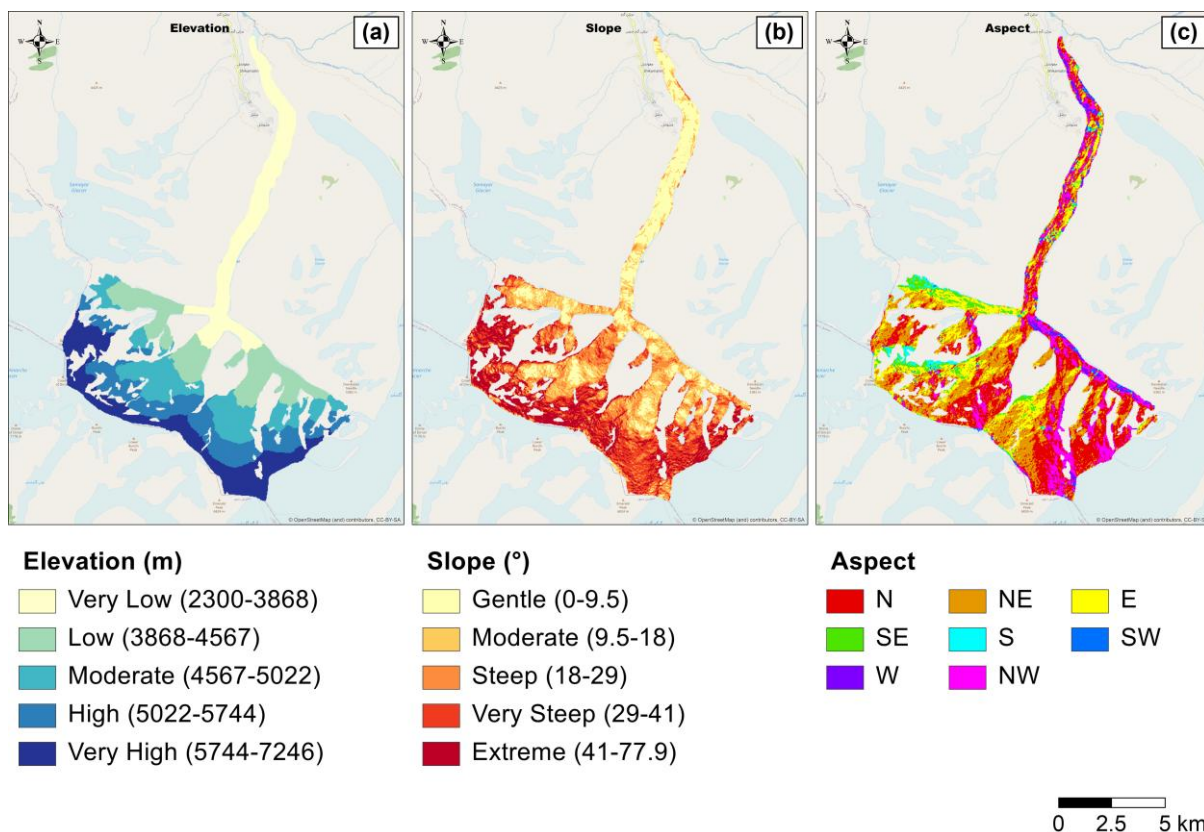


Fig. 1 Topographic setting of Bualtar Glacier derived from NASADEM at 30 m resolution and classified within the glacier outline. **a** elevation, **b** slope, **c** aspect. Elevation is lowest along the tongue running north and highest in the accumulation basin to the south. Slope follows the same division, gentle along the trunk and steep to extreme around the basin margins where the headwalls sit. Aspect is dominated by the northern sectors. Basemap © OpenStreetMap contributors, CC-BY-SA

Satellite data and pre-processing

All optical and thermal data are Landsat Collection 2 Level-2 products (U.S. Geological Survey 2020a, 2020b, 2020c). These supply atmospherically corrected surface reflectance and surface temperature. Each epoch is a pixel-wise median composite over a window centred on the nominal year. The window is ± 1 year by default. It widens to ± 2 or ± 3 years where fewer than six scenes are available, which the early epochs required. Processing was carried out in Google Earth Engine (Gorelick et al. 2017). Table 1 lists the sensors, Earth Engine collections, scene counts and observed area for each epoch.

Table 1 Sensors, collections, scene counts and observed area for each epoch. TM, Thematic Mapper; ETM+, Enhanced Thematic Mapper Plus; OLI/TIRS, Operational Land Imager/Thermal Infrared Sensor

Epoch	Sensor(s)	Earth Engine collection	Scenes	Observed (km ²)	% of outline
1990	Landsat 5 TM	LT05	12	38.05	58.9
1995	Landsat 5 TM	LT05	15	53.62	83.0
2000	Landsat 5 TM + Landsat 7 ETM+	LT05 + LE07	38	61.10	94.6
2005	Landsat 5 TM + Landsat 7 ETM+	LT05 + LE07	50	61.69	95.5
2010	Landsat 5 TM + Landsat 7 ETM+	LT05 + LE07	78	61.03	94.5
2015	Landsat 8 OLI/TIRS	LC08	54	64.56	100.0
2020	Landsat 8 + Landsat 9	LC08 + LC09	56	64.56	100.0
2025	Landsat 8 + Landsat 9	LC08 + LC09	90	64.21	99.5

Topographic parameters derive from NASADEM at 30 m resolution (NASA JPL 2020). Reference climate series come from ERA5-Land monthly 2 m air temperature (Muñoz-Sabater et al. 2021) and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) pentad precipitation (Funk et al. 2015). CHIRPS is used as a relative indicator only. It is gauge-calibrated, and rain gauges in the Karakoram are sparse and sit at low elevation.

The analysis boundary is the geometric union of the two GLIMS outlines for this glacier, dated 1997 and 2007 (GLIMS Consortium 2005; RGI Consortium 2017). The union is a deliberate choice for a surge-type glacier. The 1997 outline records Bualtar near its surge maximum; the 2007 outline records it after readjustment. Measure loss against the 2007 outline alone and terrain that carried ice inside the study period drops out, understating change. Measure against the 1997 outline alone and post-surge retreat is counted as climate-driven loss. The union keeps both. Because it also records which sub-area came from which outline, the two signals stay separable at the interpretation stage. Outline uncertainty in remote sensing is large in its own right (Paul et al. 2013; Racoviteanu et al. 2009), a further reason to fix the boundary once rather than re-delineate the glacier at every epoch.

Three pre-processing steps were applied. Scene-level cloud filtering alone is insufficient. It admits scenes that are 40 % cloudy, then composites their cloudy pixels along with everything else. Cloud is cold and bright at once, so it depresses land surface temperature (LST) and inflates the Normalised Difference Snow Index (NDSI) in the same pass. The per-pixel quality band was used to strip cloud, dilated cloud, cirrus and cloud shadow at pixel

level. The snow bit was kept. Snow is the signal being measured. Before this masking, the 1990 composite returned a maximum LST of 4.99 °C where every other epoch reached 21-32 °C, and an NDSI 5th percentile of 0.489. That implies not one bare-rock pixel anywhere on the glacier, which is physically impossible.

Landsat 8 and 9 carry an additional coastal-aerosol band, so every band index shifts by one relative to Landsat 5 and 7. Each scene is renamed to a common set of roles on load (green, red, near-infrared, shortwave-infrared-1 (SWIR1), thermal), and no later step refers to a band number. The pre-correction chain computed the Normalised Difference Vegetation Index (NDVI) as a normalised difference of surface-reflectance bands 4 and 3 for both sensor families. That is correct for Landsat 5 and 7. On Landsat 8 it computes a red-green difference, so the vegetation filter inside the debris mask ran on the wrong index for 2015, 2020 and 2025.

Collection 2 scaling factors were then applied to the stored digital numbers (DN):

$$\text{reflectance} = \text{DN} \times 0.0000275 - 0.2 \quad (1)$$

$$\text{temperature (}^{\circ}\text{C)} = \text{DN} \times 0.00341802 + 149.0 - 273.15 \quad (2)$$

Common observation footprint

The correction with the largest effect on the results concerns uneven observation coverage. Cloud masking removes pixels. It removes far more of them in epochs served by few scenes. A median composite built from six scenes leaves large parts of the glacier with no clear observation at all. Those pixels are masked, and a masked pixel counts as neither ice nor not-ice. It drops out of the area total.

Measured area then tracks satellite coverage. Run without correction, this processing chain returned a glacier extent of roughly 20 km² for 1990 and 47 km² for 2000. More than double in ten years. No glacier does that. Both totals followed the number of scenes available.

An observation count was computed for every pixel in every epoch. The analysis was then restricted to pixels observed at least once in all eight epochs. This common footprint covers 37.08 km², 57.4 % of the 64.56 km² outline (Fig. 2). Every parameter reported below is computed on that identical pixel set. That is what makes the epochs comparable, and what makes agreement between parameters mean anything.

The common footprint costs 43 % of the glacier outline. With a July-September ablation window the 1990 epoch observed only 17 % of the glacier, and the common footprint collapsed to 9.6 km², 14.9 % of the outline. Dropping the 1990 and 1995 epochs would have sacrificed the surge period. Widening the window to June-October, with a one-observation minimum, gave the best available compromise at 37.08 km².



Fig. 2 Cloud-free ground observed in each of the eight epochs, plotted against the full 64.56 km² glacier outline and against the 37.08 km² footprint common to all epochs. Observed area rises from 38.05 km² in 1990, 58.9 % of the outline, to the full outline in 2015 and 2020. The 1990 and 1995 epochs therefore see far less of the glacier than later epochs. Restricting every epoch to the common footprint, marked by the red line, is what makes the series internally comparable; without that restriction, measured area tracks scene availability rather than ice

Parameter derivation

NDSI is computed from the green and shortwave-infrared bands:

$$\text{NDSI} = (\text{green} - \text{SWIR1}) / (\text{green} + \text{SWIR1}) \quad (3)$$

Ice and snow are taken at the conventional threshold $\text{NDSI} \geq 0.4$ (Hall et al. 1995). The threshold is applied to the ablation-season composite, not to the spring composite. Output is a binary ice mask per epoch, and that mask feeds both the extent totals and the four-class change coding.

LST is taken directly from the Collection 2 surface temperature (ST) product and converted to degrees Celsius. This is a radiometric surface temperature. It is not air temperature. Over a

glacier LST responds strongly to debris cover, to which the Limitations section returns as a limit on the convergence argument.

Debris is identified as pixels simultaneously warm ($LST > 0\text{ }^{\circ}\text{C}$), not snow-covered ($NDSI < 0.4$) and not vegetated ($NDVI < 0.2$). The resulting binary layer separates debris from non-debris. It does not separate clean ice from unobserved ground. Those two were split by reading the NDSI layer beneath, since NDSI carries the observation mask.

The snowline proxy is the 10th percentile of the elevation of ice-covered pixels at the end of the ablation season. It is a proxy for the equilibrium line altitude, not a measurement of one. No mass-balance data were available to validate it.

Four change classes are coded jointly from the two epochs' ice masks rather than by subtracting them: non-glacier (ice in neither year), loss (ice in the first year only), stable (ice in both), and gain (ice in the second year only). The Discussion sets out why the joint coding matters.

Cartographic production

A total of 43 map sheets were produced in ArcGIS 10.8 at 600 dpi. Class breaks are pooled across all epochs. One colour denotes one value on every sheet, and that is what permits visual comparison between years. Colour schemes come from ColorBrewer (Harrower and Brewer 2003) and are colour-blind safe: RdYlBu for temperature, BrBG for NDSI, RdBu with Greys for change classes, YlGnBu for elevation, YlOrRd for slope. Full class breaks and RGB values for every layer are given in Tables S1-S4 (Online Resource 1).

Use of AI tools

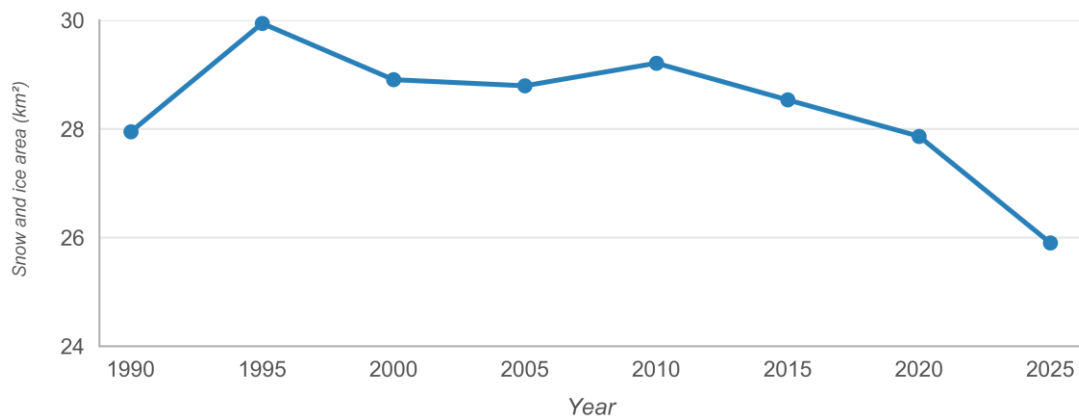
An AI assistant (Claude, Anthropic) was used for help with code (the Earth Engine script and the plotting scripts) and for language editing. The authors checked all such output and take full responsibility for the content.

Results

Ice extent and surface temperature

Snow- and ice-covered area within the common footprint fell from 27.95 km² in 1990 to 25.90 km² in 2025. That is 2.05 km², or 7.3 %. As a share of observed ground the decline runs from 75.1 % to 69.7 %. The fitted trend is -0.61 km² per decade. With $r^2 = 0.377$ and

207 $p = 0.106$ it is not significant at the 5 % level. The series stays close to flat between 1995 and
 208 2015, then falls (Fig. 3).



209 **Fig. 3** Snow- and ice-covered area within the common 37.08 km² footprint, 1990-2025. Extent falls from
 210 27.95 km² to 25.90 km², a reduction of 2.05 km² or 7.3 %. As a share of observed ground the decline runs from
 211 75.1 % to 69.7 %. The fitted trend of -0.61 km² per decade is not significant at the 5 % level ($r^2 = 0.377$,
 212 $p = 0.106$). The decline is not linear: the series holds close to flat between 1995 and 2015, then falls in the final
 213 decade
 214

215 Mean glacier-surface temperature rose from -0.14 °C in 1990 to 4.82 °C in 2025. The least-
 216 squares trend is +1.88 °C per decade, $r^2 = 0.756$, $p = 0.005$. Across eight epochs this is the
 217 only glaciological parameter whose trend clears conventional significance. The series is
 218 plotted in Fig. 4.

219 The 1995 value of -3.59 °C lies well below the surrounding epochs. Treat it with caution.
 220 That epoch rests on 15 scenes and observed 83 % of the outline. Excluding it changes neither
 221 the sign nor the significance of the trend. Surface temperature across the glacier at each epoch
 222 is mapped in Fig. 5.

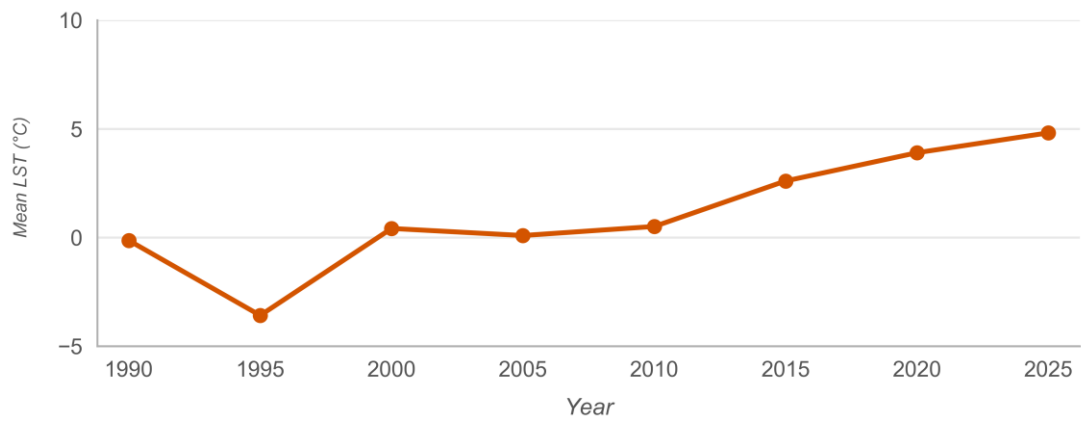


Fig. 4 Mean land surface temperature over the common footprint, 1990-2025. Temperature rises from -0.14 °C to 4.82 °C, a least-squares trend of +1.88 °C per decade ($r^2 = 0.756$, $p = 0.005$). This is the only glaciological parameter in the study whose trend clears conventional significance at an eight-epoch sample size. The 1995 value of -3.59 °C rests on 15 scenes covering 83 % of the outline and should be treated with caution; excluding it changes neither the sign nor the significance of the trend

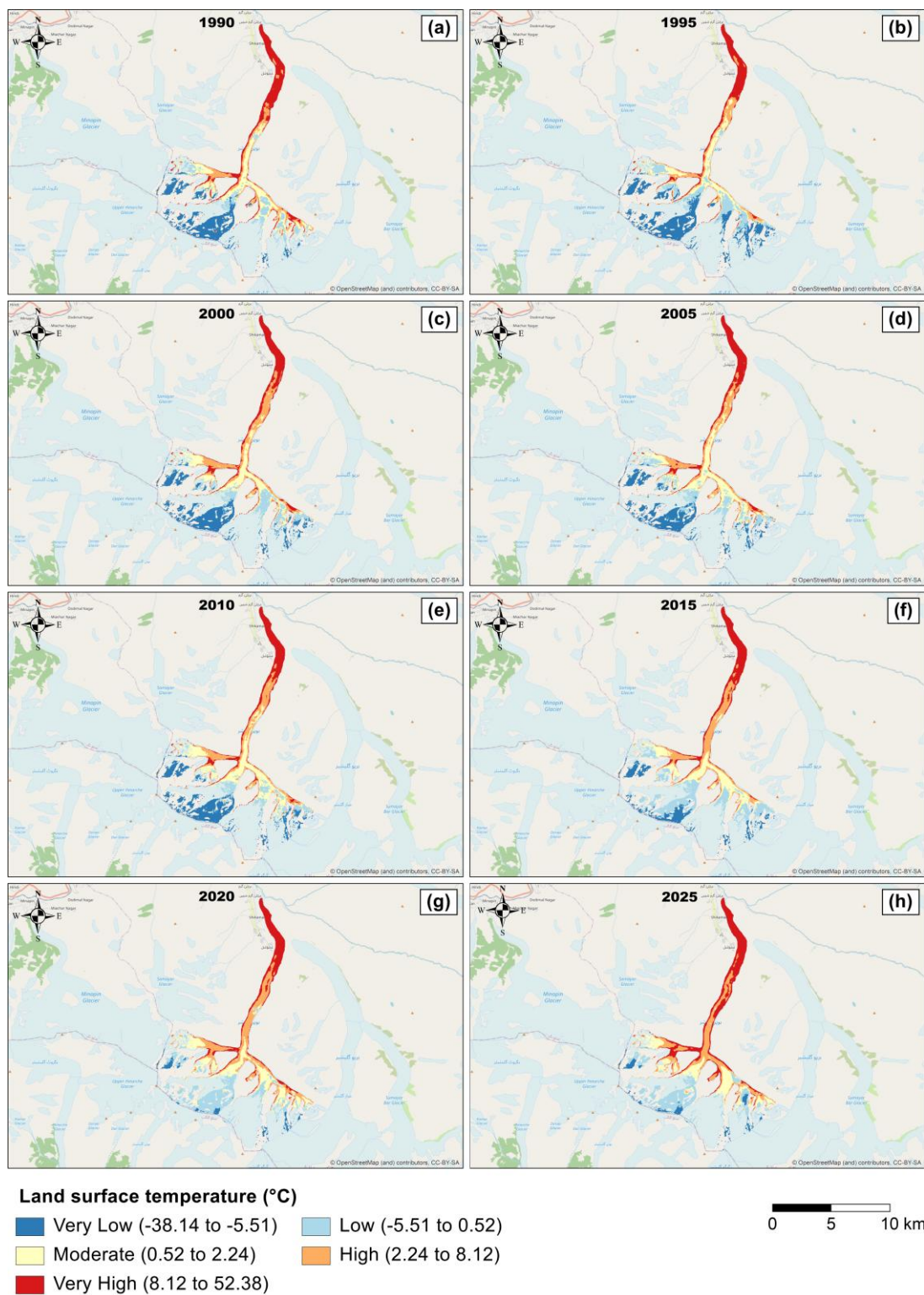


Fig. 5 Land surface temperature across the glacier at each of the eight epochs. **a** 1990, **b** 1995, **c** 2000, **d** 2005, **e** 2010, **f** 2015, **g** 2020, **h** 2025. Class breaks are pooled across all epochs, so a given colour denotes the same temperature range on every panel: blue shades mark surfaces below 0.52 °C, pale yellow the 0.52-2.24 °C range, and orange to red surfaces above 2.24 °C. The tongue stays in the warmest classes throughout the record, while the accumulation basin shifts from the coldest class into the Low class from panel **f** onward. Basemap © OpenStreetMap contributors, CC-BY-SA

NDSI and snowline altitude

Mean NDSI is flat across most of the record, 0.629 to 0.679. It falls to 0.590 in 2025. That is the lowest value in the series (Fig. 6). The fitted trend is not significant ($p = 0.424$). The 2025 value is consistent with the reduction in ice extent and the expansion of debris reported below. The per-epoch NDSI maps are given in Fig. 7.

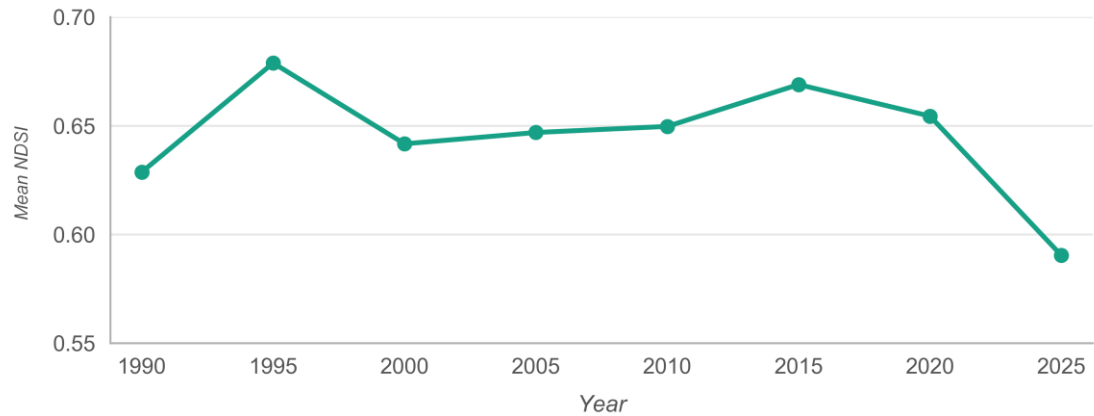


Fig. 6 Mean Normalised Difference Snow Index over the common footprint, 1990-2025. NDSI is flat across most of the record, between 0.629 and 0.679, and falls to 0.590 in 2025, its lowest value in the series. The fitted trend is not significant ($p = 0.424$). The 2025 value is consistent with the reduction in ice extent and the expansion of supraglacial debris reported in the same year

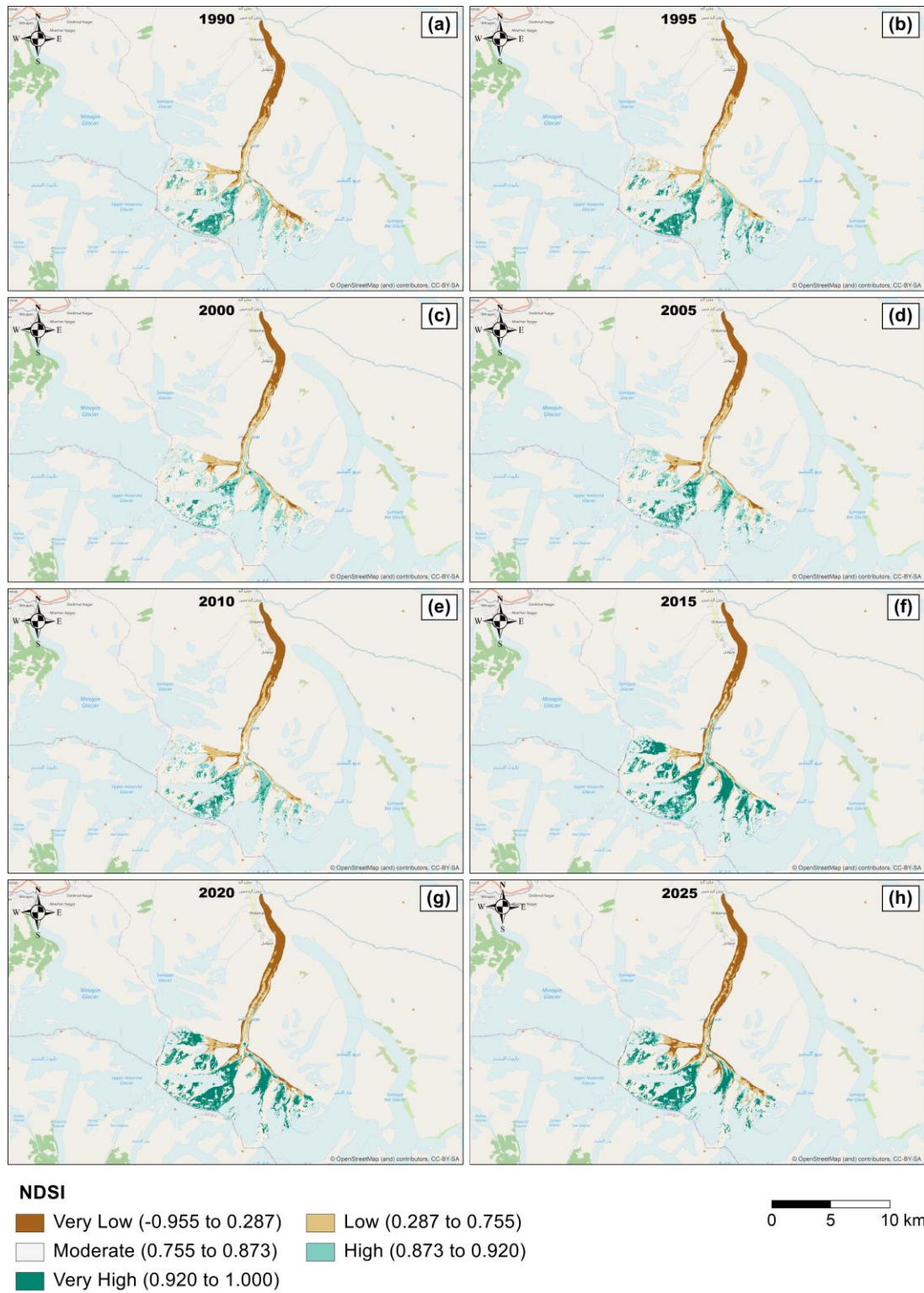


Fig. 7 Normalised Difference Snow Index across the glacier at each of the eight epochs. **a** 1990, **b** 1995, **c** 2000, **d** 2005, **e** 2010, **f** 2015, **g** 2020, **h** 2025. Class breaks are pooled across all epochs and follow the ColorBrewer BrBG scheme: dark brown marks NDSI below 0.287, tan and white the 0.287-0.873 range, and green shades values above 0.873. Ice and snow are identified at the conventional threshold $\text{NDSI} \geq 0.4$. The lower tongue stays in the brown classes in every panel; the green classes are most extensive across the accumulation basin in panels **f** and **g** and contract in **h**, matching the 2025 minimum in Fig. 6. Basemap © OpenStreetMap contributors, CC-BY-SA

The transient snowline proxy rose from 3463 m in 1990 to 3553 m in 2025. Net increase 90 m. The fitted rate is 33 m per decade ($r^2 = 0.241$, $p = 0.216$). The series is noisy and the trend is not significant. It is reported for completeness, and because its direction matches the temperature record, not as an independent result (Fig. 8).

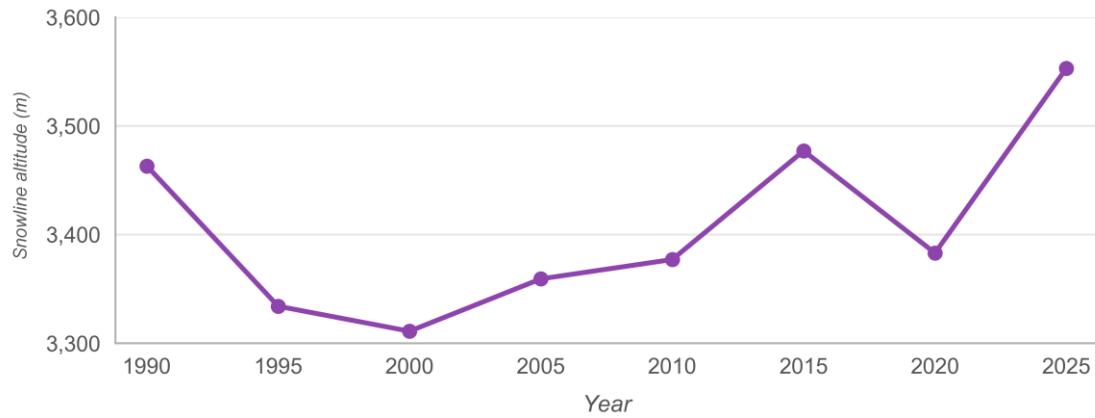


Fig. 8 Transient snowline altitude used as a proxy for the equilibrium line altitude, 1990-2025. The proxy is taken as the 10th percentile of the elevation of ice-covered pixels at the end of the ablation season. It rises from 3463 m in 1990 to 3553 m in 2025, a net increase of 90 m, at a fitted rate of 33 m per decade ($r^2 = 0.241$, $p = 0.216$). The series is noisy and the trend is not significant; it is reported because its direction matches the temperature record, not as an independent result

Supraglacial debris

Debris covered 24.8 % of the glacier surface in 1990 and 29.8 % in 2025. Between 1995 and 2015 the share held inside a narrow band, 19.4 to 22.6 %. It rose to 23.7 % by 2020. It reached 29.8 % by 2025. Between 2015 and 2025 alone the share rose 8.2 points, more than the net change across the whole record (Fig. 9). Debris and clean ice are mapped for each epoch in Fig. 10.

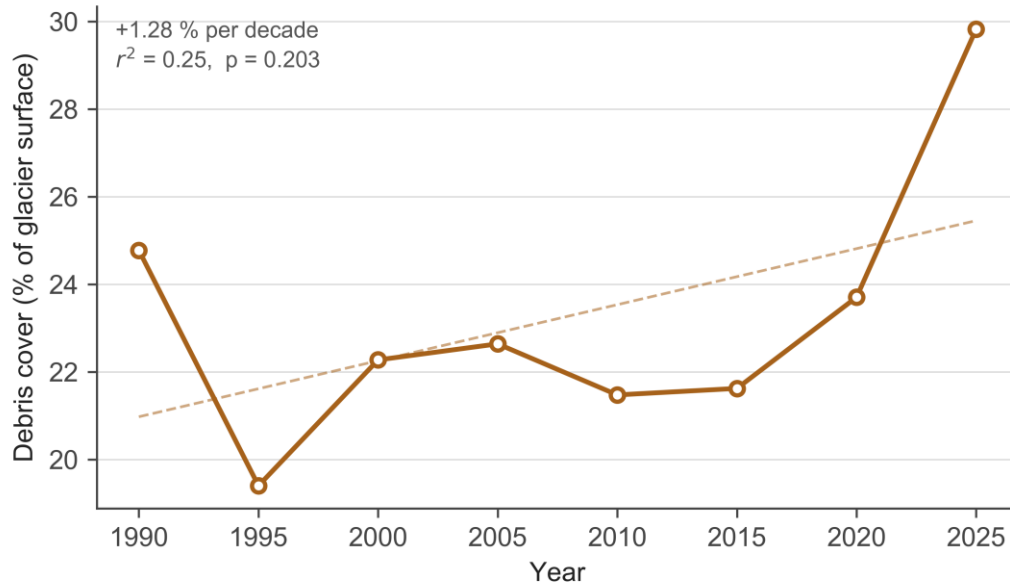


Fig. 9 Share of the glacier surface carrying supraglacial debris, 1990-2025. Debris covers 24.8 % of the surface in 1990 and 29.8 % in 2025. Between 1995 and 2015 the share holds inside a narrow band of 19.4 to 22.6 %, rises to 23.7 % by 2020, and reaches 29.8 % by 2025. Between 2015 and 2025 alone the share rose 8.2 points, more than the net change across the whole record. Debris is identified as pixels simultaneously warm, not snow-covered and not vegetated. The dashed line is the least-squares trend (+1.28 % per decade, $r^2 = 0.25$, $p = 0.203$), which is not significant

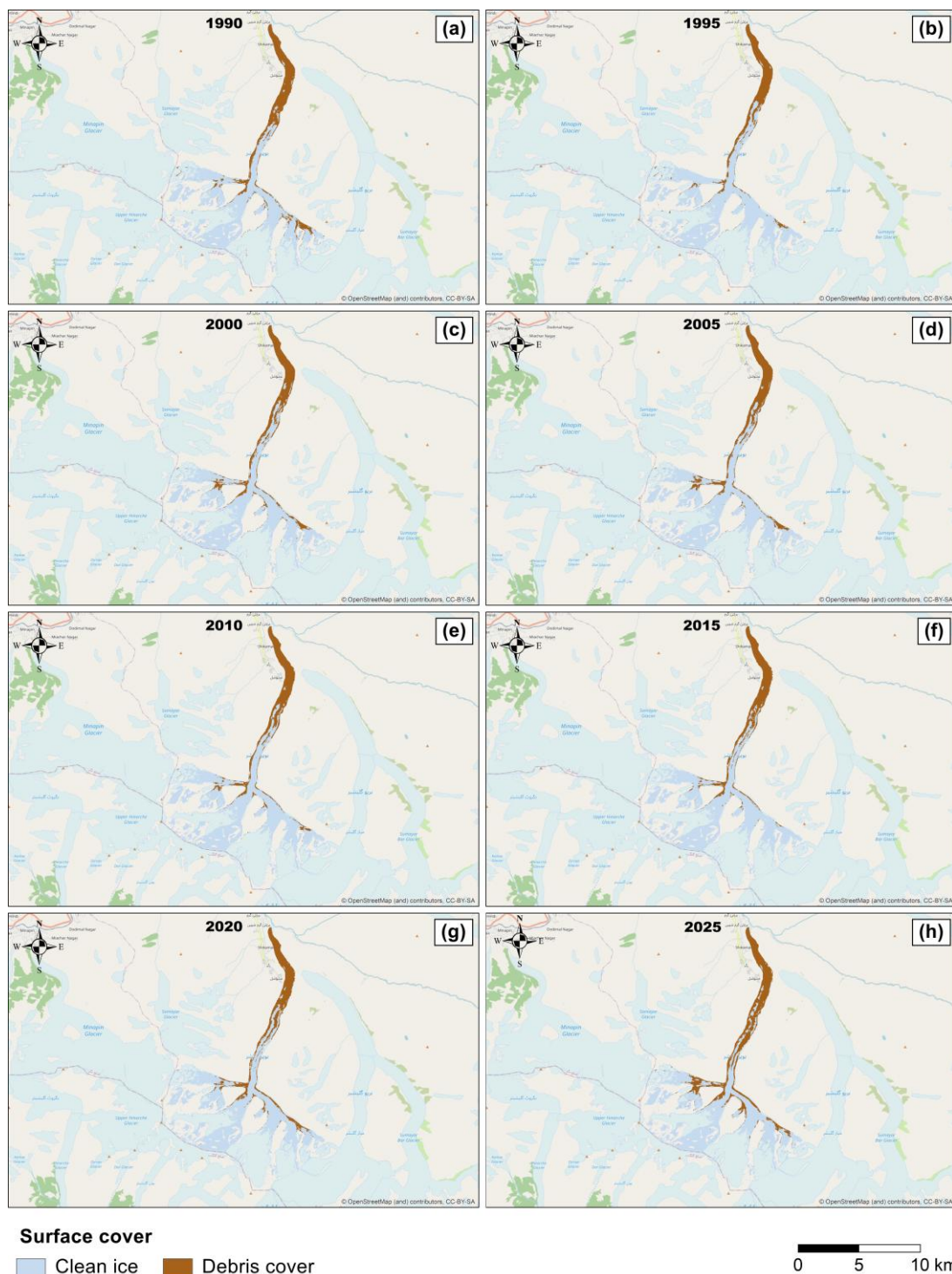


Fig. 10 Supraglacial debris and clean ice across the glacier at each of the eight epochs. **a** 1990, **b** 1995, **c** 2000, **d** 2005, **e** 2010, **f** 2015, **g** 2020, **h** 2025. Brown marks debris cover and pale blue marks clean ice; ground outside the common observation footprint is rendered transparent. The lower tongue is debris-covered in every panel; by panel **h** debris also spreads onto the tributary junctions, and across panels **f** to **h** the debris share rises from 21.6 % to 29.8 %. Basemap © OpenStreetMap contributors, CC-BY-SA

Seasonal snow cover

Spring snow-covered area rises from roughly 10 km² in 1990-1995 to 24 km² in 2000-2010 and 32 km² in 2015-2025. This series returns the strongest statistical trend in the study: +6.79 km² per decade, $r^2 = 0.844$, $p = 0.001$. It is not a glaciological result. The three levels match the three sensor eras: Landsat 5 alone, Landsat 5 with 7, Landsat 8 with 9. The common footprint was derived from ablation-season observations and does not constrain spring coverage, so in epochs with sparse spring imagery unobserved ground counts as snow-free. What the series measures is improving satellite coverage of the spring season. It is reported here so the artefact stays on the record instead of being dropped in silence (Fig. 11). The corresponding maps are given in Fig. 12.

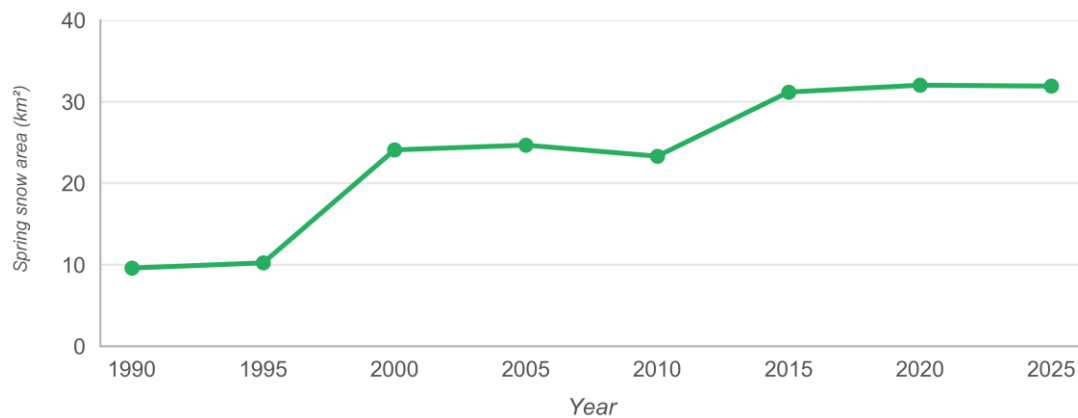


Fig. 11 Spring snow-covered area, 1990-2025. The series rises from roughly 10 km² in 1990-1995 to 24 km² in 2000-2010 and 32 km² in 2015-2025, and returns the strongest statistical trend in the study (+6.79 km² per decade, $r^2 = 0.844$, $p = 0.001$). The three levels correspond to Landsat 5 alone, Landsat 5 with 7, and Landsat 8 with 9. What the series measures is improving satellite coverage of the spring season, not increasing snowfall, and it is not interpreted as a glaciological result

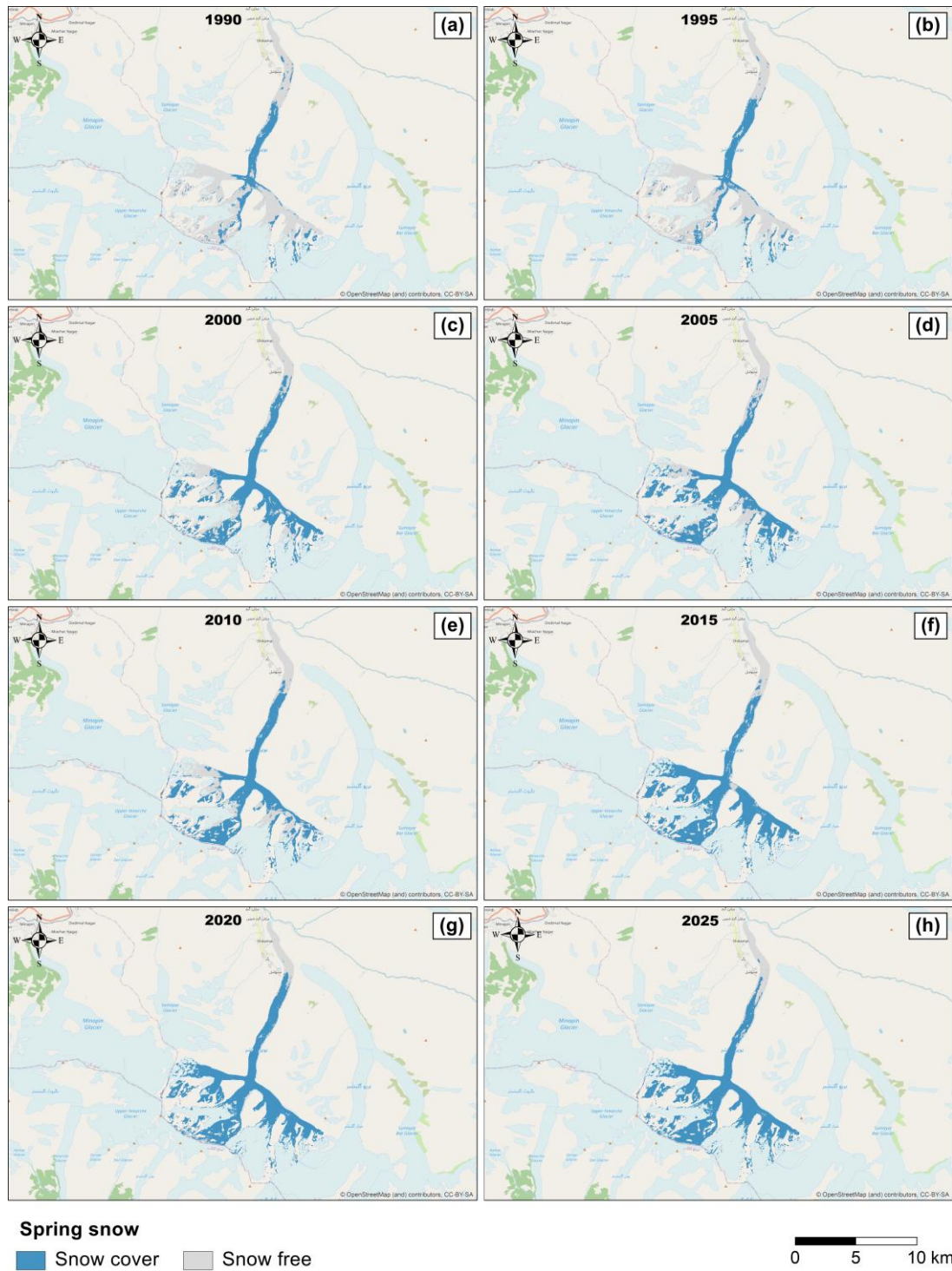


Fig. 12 Spring snow cover across the glacier at each of the eight epochs. **a** 1990, **b** 1995, **c** 2000, **d** 2005, **e** 2010, **f** 2015, **g** 2020, **h** 2025. Blue marks snow cover and grey marks snow-free ground. These panels are presented for completeness only. The common footprint was derived from ablation-season observations and does not constrain spring coverage, so in epochs with sparse spring imagery unobserved ground counts as snow-free and the apparent increase is an artefact of sensor availability. Basemap © OpenStreetMap contributors, CC-BY-SA

Reference climate series

ERA5-Land monthly 2 m air temperature and CHIRPS pentad precipitation are shown for regional context. Neither is used quantitatively. ERA5-Land is a reanalysis at roughly 9 km resolution (Muñoz-Sabater et al. 2021), so Bualtar occupies one or two grid cells. CHIRPS under-represents high-altitude snowfall for the reasons given above. Both series are read for direction only, and both are shown in Figs. 13 and 14.

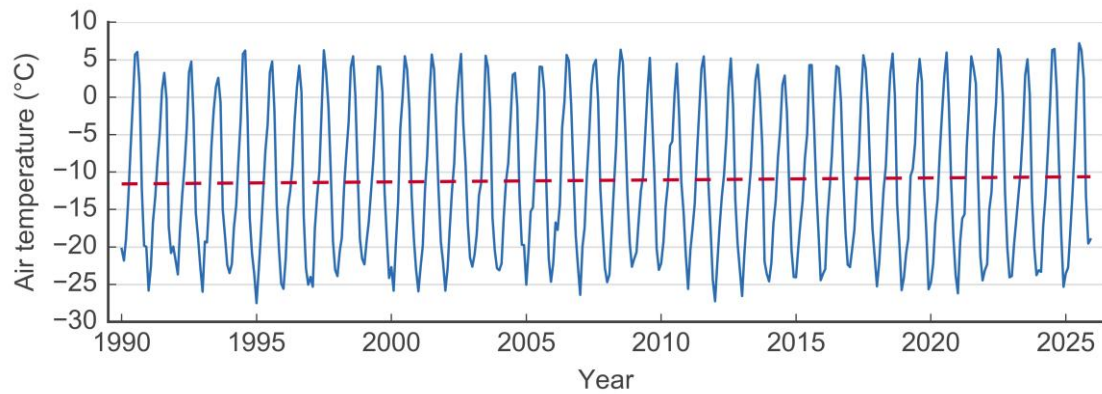


Fig. 13 ERA5-Land monthly 2 m air temperature over the glacier, 1990-2025, shown as regional context. The series is not used quantitatively. ERA5-Land is a reanalysis at roughly 9 km resolution, so Bualtar occupies only one or two grid cells and the record cannot resolve conditions on the glacier surface itself. It is read for direction only, alongside the surface temperature record in Fig. 4. The dashed line is the least-squares linear trend

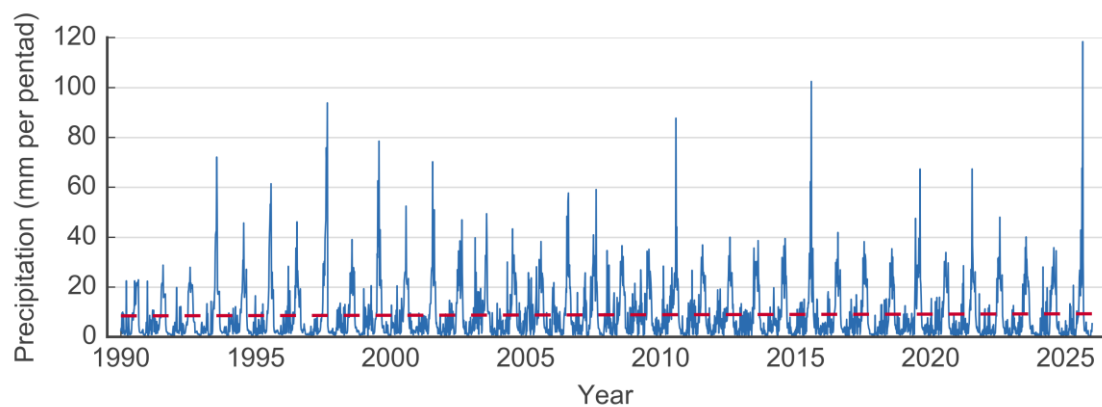


Fig. 14 CHIRPS pentad precipitation over the glacier, 1990-2025, shown as a relative trend and as regional context only. CHIRPS is calibrated on rain gauges, and in the Karakoram those gauges are sparse and situated at low elevation, so the product under-represents high-altitude snowfall. The series is read for direction only and carries no quantitative weight in the analysis. The dashed line is the least-squares linear trend

Surface change classification

Table 2 Per-epoch summary of all comparable parameters, computed on the common 37.08 km² footprint. Ice (%) and Debris (%) are shares of the ground observed in each epoch

Year	Mean LST (°C)	Max LST (°C)	Mean NDSI	Ice (km ²)	Ice (%)	Debris (%)	Snowline (m)
1990	-0.14	52.38	0.629	27.95	75.1	24.8	3463
1995	-3.59	28.05	0.679	29.94	80.5	19.4	3334
2000	0.42	33.36	0.642	28.91	77.7	22.3	3311
2005	0.09	35.08	0.647	28.79	77.3	22.6	3359
2010	0.51	34.14	0.650	29.21	78.4	21.5	3377
2015	2.60	33.30	0.669	28.53	77.6	21.6	3477
2020	3.90	32.89	0.654	27.86	75.6	23.7	3383
2025	4.82	35.20	0.590	25.90	69.7	29.8	3553

Table 3 Four-class surface change composition, as a percentage of the common footprint

Interval	Non-glacier	Loss	Stable	Gain	Net	Loss rate (% yr ⁻¹)
1990-1995	18.5	1.0	74.1	6.5	+5.4	0.20
1995-2000	17.7	4.6	75.9	1.7	-2.9	0.92
2000-2005	20.1	2.6	75.1	2.2	-0.4	0.52
2005-2010	20.0	1.6	75.7	2.7	+1.1	0.32
2010-2015	19.8	2.5	75.7	1.9	-0.6	0.50
2015-2020	20.8	3.8	73.7	1.7	-2.2	0.77
2020-2025	23.0	7.4	68.2	1.4	-6.0	1.48
1990-2025	21.3	9.0	66.0	3.7	-5.3	0.26

Table 2 summarises every parameter by epoch and Table 3 gives the four-class composition of each interval (Fig. 15). Across the full 35-year period, 9.0 % of the common footprint lost ice and 3.7 % gained it (Table 3). Net loss 5.3 %. The interval breakdown carries more than the total does. Loss rates ran between 0.20 and 0.92 % per year for every interval from 1990 to 2015. The 2015-2020 interval reached 0.77 % per year (Fig. 16). The 2020-2025 interval reached 1.48 % per year, 1.6 times the highest earlier interval and about three times the mean of the 1990-2015 intervals.

The 1990-1995 interval carries by far the largest net gain in the record, +5.4 %; the only other positive interval is 2005-2010, at +1.1 %. That fits the surge history. Gain of this kind is the

dynamic signature of an advancing front. The four classes are mapped for every interval in Fig. 17.

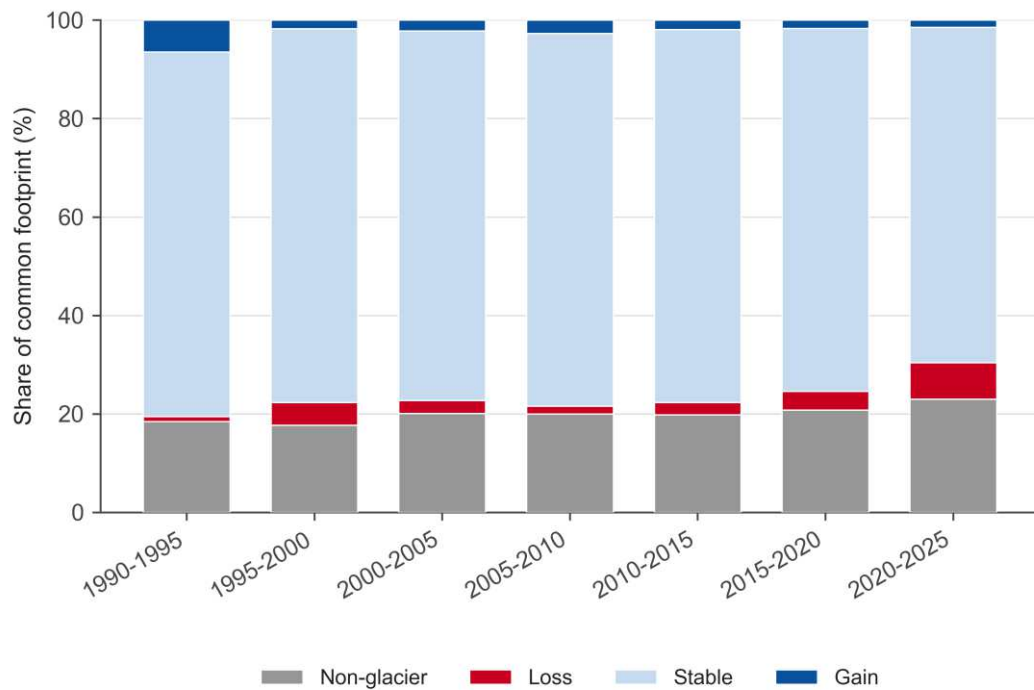


Fig. 15 Surface-class composition of each five-year interval, expressed as a percentage of the common 37.08 km² footprint. Four classes are coded jointly from the two epochs' ice masks: non-glacier, loss, stable and gain. The stable class contracts and the loss class expands in the final two intervals, falling from 75.7 % stable in 2010-2015 to 68.2 % in 2020-2025 while loss rises from 2.5 % to 7.4 %. The 1990-1995 interval carries by far the largest net gain in the record, +5.4 %

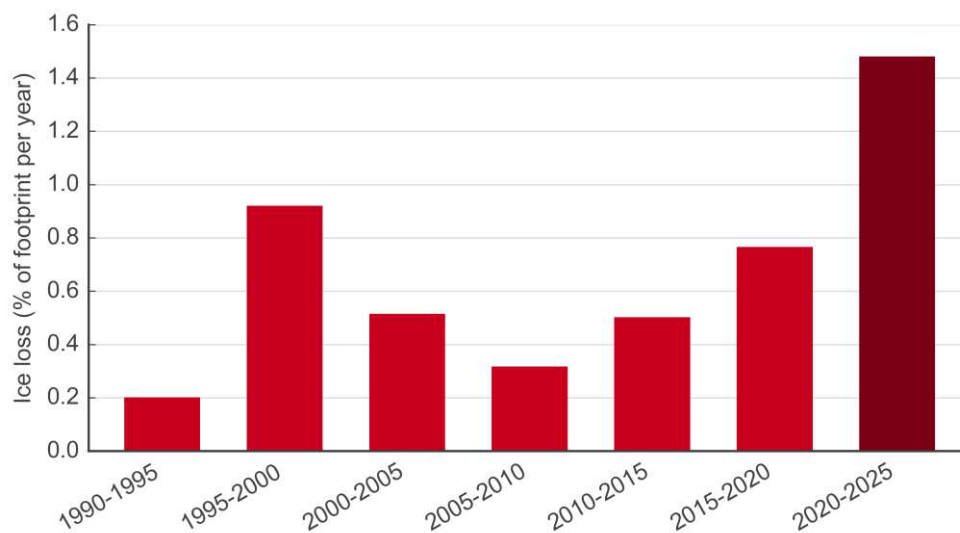
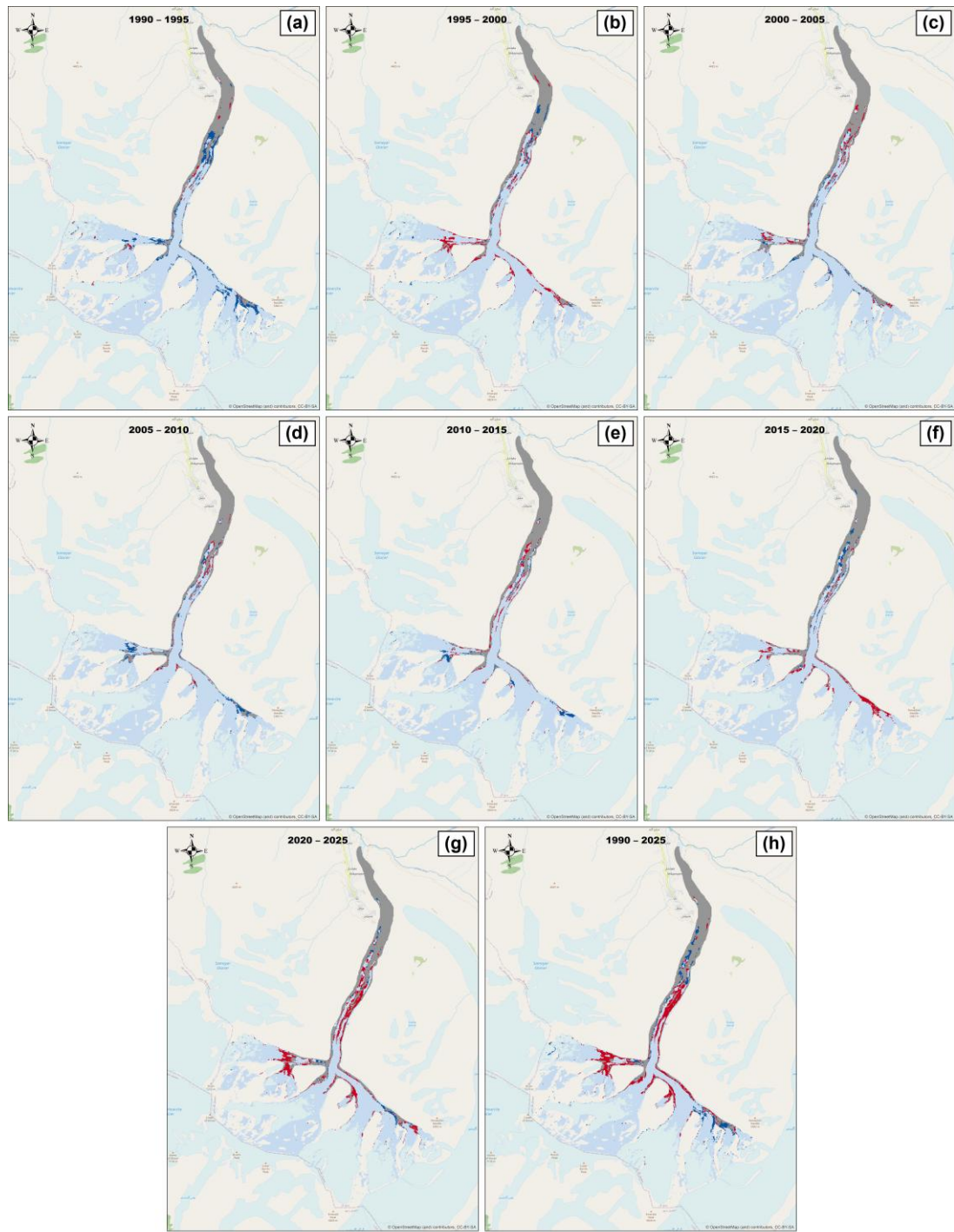


Fig. 16 Annualised ice loss rate by interval, as a percentage of the common footprint per year. Loss rates run between 0.20 and 0.92 % per year for every interval from 1990 to 2015. The 2015-2020 interval reaches 0.77 % per year and the 2020-2025 interval reaches 1.48 % per year, 1.6 times the highest earlier interval and about three times the mean of the 1990-2015 intervals. This is the clearest single expression of the post-2015 break



Change class

Non-glacier
 Loss
 Stable
 Gain

0 2.5 5 km

Fig. 17 Four-class surface change for each interval in the record. **a** 1990-1995, **b** 1995-2000, **c** 2000-2005, **d** 2005-2010, **e** 2010-2015, **f** 2015-2020, **g** 2020-2025, **h** 1990-2025. Grey marks ground that held no ice in either year, red marks loss, pale blue marks ice present in both years, and dark blue marks gain. Blue gain is most extensive in **a**, the interval that overlaps the surge, which is the dynamic signature of an advancing front. Among the five-year intervals, red loss is most extensive in **g**, the interval with the highest loss rate in the record at 1.48 % per year. Basemap © OpenStreetMap contributors, CC-BY-SA

Topographic setting

North- and northeast-facing terrain together take 59.1 % of the glacier surface, 19.61 and 17.87 km² respectively. South- and southwest-facing terrain takes 3.3 %. The full distribution across the eight compass sectors is given in Table 4 and plotted in Fig. 18.

Table 4 Distribution of glacier surface aspect, from the NASADEM pixels within the outline

Sector	Area (km ²)	Share (%)
North	19.61	30.94
Northeast	17.87	28.20
East	9.68	15.28
Northwest	8.38	13.22
Southeast	3.48	5.49
West	2.29	3.61
South	1.44	2.28
Southwest	0.63	1.00

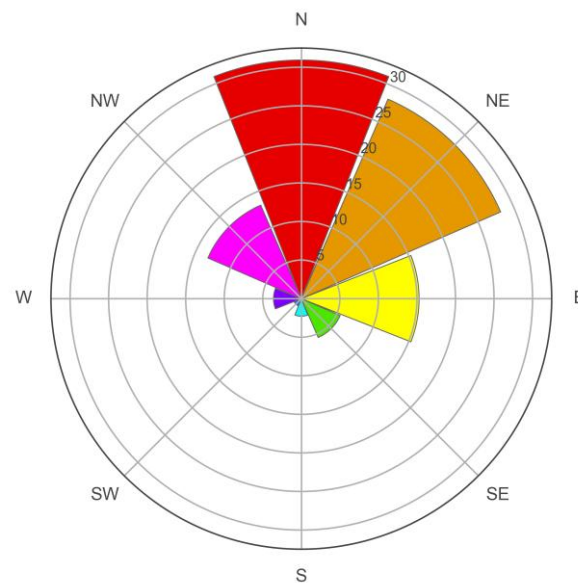


Fig. 18 Aspect distribution of the glacier surface, binned into eight compass sectors from NASADEM; bar length gives each sector's share of the surface (%). North accounts for 19.61 km² and northeast for 17.87 km², together 59.1 % of the surface. South and southwest together account for 2.07 km², or 3.3 %. Nearly three fifths of the glacier therefore faces the aspects that receive least direct solar radiation, which bears directly on its survival

Discussion

Individually, no interpretable parameter except temperature produces a significant trend across eight epochs. A reader could stop there and conclude that the record is too short and

too noisy to carry a claim. That conclusion would be defensible. The argument advanced here rests on something else: agreement between parameters measured independently of one another.

LST derives from the thermal band. Ice extent derives from the green and shortwave-infrared bands. Debris cover combines thermal, shortwave-infrared, red and near-infrared. LST and ice extent are different physical measurements of one surface and carry largely independent error. Debris cover is less independent: within the common footprint almost every pixel that is not ice is classed as debris, so the ice and debris shares are close to complementary (Table 2). Between 2015 and 2025 every one of them moves in the direction warming would produce. Mean LST rises from 2.60 °C to 4.82 °C, an increase of 2.21 °C in ten years against 2.74 °C across the preceding 25 years. Ice extent falls from 28.53 km² to 25.90 km², a reduction of 2.63 km², having fallen only 1.41 km² over 1995-2015. Debris rises from 21.6 % to 29.8 %, a gain of 8.2 points against a loss of 3.2 points over 1990-2015. Mean NDSI falls to its lowest value in the series, and the interval loss rate roughly doubles.

A single index can drift for instrumental reasons. Five measurements drawn from four spectral regions, drifting together, in the direction one mechanism predicts, at the same time, are much harder to write off as artefact. The conclusion here rests on that convergence (Fig. 19).

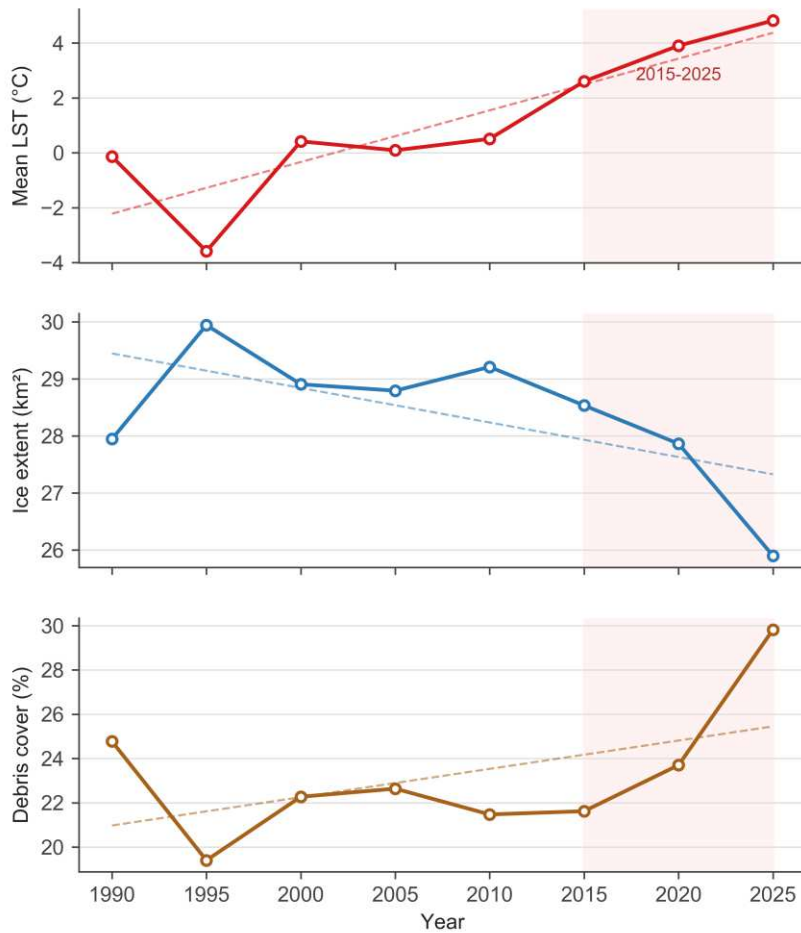


Fig. 19 Three separately measured parameters plotted on a common time axis: mean land surface temperature, snow- and ice-covered extent, and supraglacial debris share. LST derives from the thermal band, ice extent from the green and shortwave-infrared bands, and debris cover from a combination of thermal, shortwave-infrared, red and near-infrared. The shaded band marks 2015-2025, where all three depart from their earlier behaviour in the direction warming would produce. This convergence, above all between the thermal (LST) and reflective (ice extent) measurements, rather than any individual p-value, is the basis for the conclusion. Dashed lines are least-squares trends over 1990-2025

Bualtar's surge history complicates any straightforward reading of area change. Surge behaviour at this glacier is in the published record, with active surges in 1987 and 1990 (Bhambri et al. 2017; Gardner and Hewitt 1990). The Karakoram as a whole carries an exceptional concentration of surge-type ice (Bhambri et al. 2017; Copland et al. 2011; Quincey et al. 2011).

The 15.99 km² that appears in the 1997 GLIMS outline and not in the 2007 outline is, by construction, terrain Bualtar occupied at its surge maximum and had vacated ten years later. Retreat across that area is dynamic readjustment. A surge front advances fast, stagnates, then downwastes, and climate has little to do with any of it. Attributing that retreat to warming would be an error.

Two observations indicate the post-2015 signal is not of this kind. First, the timing is wrong. The surge and its immediate readjustment fall in the 1990-2005 window. The acceleration reported here begins two decades later, by which point post-surge downwasting would have largely run its course. Second, the 1990-1995 interval, the one interval that does overlap the surge, carries by far the largest net gain in the record, +5.4 %. That is the dynamic signature of an advancing glacier, and the opposite of the late-record behaviour.

The 9.0 % gross loss over 1990-2025 therefore contains a dynamic component in its early portion and a climate-consistent component in its later portion. The two should not be read as one number. The 2020-2025 interval rate of 1.48 % per year is the cleaner climate indicator.

Five findings here depart from existing work, four methodological and one glaciological.

The conventional formulation for NDSI-based change detection is a subtraction:

$$\text{change} = (\text{NDSI}_2 \geq 0.4) - (\text{NDSI}_1 \geq 0.4) \quad (4)$$

Equation (4) returns -1 for loss, +1 for gain, and 0 for everything else. The difficulty is what “everything else” contains. Ice present in both years gives $1 - 1 = 0$. Bare rock present in both years gives $0 - 0 = 0$. The two are indistinguishable in the output, and both are conventionally reported as “stable”.

Coding the two ice masks jointly rather than subtracting them separates the cases at no extra data cost. This is the from-to logic of post-classification comparison, long standard in land-cover change detection (Lu et al. 2004). The point here is how far the subtraction shortcut misstates glacier stability when it is used instead. On Bualtar the difference is large. The subtraction form reports 92.5 % stable for 1990-1995. The four-class form reports 74.1 % stable, with a further 18.5 % identified as non-glacier terrain. A stability figure of 92.5 % for a Karakoram glacier is the kind of number that feeds an anomaly narrative, and roughly one fifth of it here is ground without clean ice. Most glacier outlines include non-glaciated terrain, and union boundaries and basin masks include a great deal of it. Any study applying the subtraction form on such a boundary reports a stability figure inflated by the non-glaciated fraction, and nothing in the output reveals the inflation.

The second finding has the largest practical consequence, and it came to light only because the uncorrected result was physically impossible. Run without an observation-count constraint, this processing chain returned 20 km² of ice for 1990 and 47 km² for 2000. No

glacier more than doubles in ten years. The measured quantity was correlating with the number of usable Landsat scenes, not with ice. Per-pixel cloud masking removes observations, and removes disproportionately many in epochs served by few scenes, a known property of pixel-based compositing (White et al. 2014). A masked pixel contributes to neither the ice class nor the not-ice class. It leaves the area total altogether. Early epochs then report the area of ice that happened to be observed, which is smaller than the area of ice. The 1990 epoch observed 38.05 km² of the 64.56 km² outline, 58.9 %, while 2015 and 2020 observed 100 %. Restricting every epoch to the 37.08 km² observed in all epochs removes the bias, at the cost of 43 % of the outline. The problem is invisible in the output. An uncorrected series looks like a plausible trend. It simply has the wrong magnitude in the early decades. Landsat coverage over the Karakoram improved a great deal between the 1990s and the 2010s, so any long-record study of this region that applies per-pixel cloud masking without a coverage constraint will tend to underestimate early-period ice area and so report a spurious increase over time. In this region such a bias leads directly to the conclusion that glaciers were stable or growing.

The third finding follows from the second. Coverage varied here from 58.9 % to 100 % of the outline across epochs. A paper reporting only final areas gives its reader no way to detect the problem described above. Table 1 reports scene count and observed area for every epoch; Fig. 2 shows the same thing graphically. The cost is one table row per epoch. The gain is that a reader can judge how much weight each epoch carries. Existing recommendations on reporting glacier-mapping uncertainty point the same way (Paul et al. 2013; Racoviteanu et al. 2009).

The fourth concerns the analysis boundary. The area changes of surge-type glaciers confound climate interpretation, and new approaches are needed to account for them (Bhambri et al. 2017). Setting them aside would remove a large fraction of Karakoram ice from the record (Bhambri et al. 2017; Copland et al. 2011), including the very glaciers whose behaviour is most often invoked to explain the anomaly. The approach used here keeps the glacier and partitions the boundary instead. The union boundary records which sub-area came from the 1997 outline and which from 2007, so the 15.99 km² of surge-maximum terrain stays identifiable. Change inside it can be discounted or reported on its own. Set against the interval-by-interval loss rates in Table 3, that makes it possible to say which part of the record is dynamically contaminated (1990-2005) and which is not (2015-2025).

The glaciological finding is that Bualtar's record splits cleanly in two. From 1990 to 2015, the period most of the anomaly literature covers (Bolch et al. 2012; Gardelle et al. 2012; Hewitt 2005), ice extent is flat within noise: 29.94 km² in 1995 against 28.53 km² in 2015. Debris cover oscillates without trend. Interval loss rates stay between 0.20 and 0.92 % per year. This study reproduces Karakoram stability over the period the anomaly was described for, on a fully independent processing chain. From 2015 to 2025 every interpreted parameter departs from that pattern at once. Reproducing the earlier stability first is what makes the departure hard to dismiss as a processing difference: the same chain that returns stability for 1990-2015 returns acceleration for 2015-2025. Table 5 sets out where this study departs from common practice in comparable work.

Table 5 Points of departure from common practice in comparable studies

Aspect	Common practice	This study
Change classes	Three classes from a difference image; stable class includes non-glaciated ground	Four classes coded jointly; stable class contains only ice present in both epochs
Uneven cloud coverage	Cloud-masked composites used directly; coverage often not reported	Common observation footprint enforced across all epochs; coverage tabulated
Surge-type glaciers	Area changes hard to attribute to climate	Retained, with the boundary partitioned so dynamic and climatic change are separable
Parameter independence	Parameters reported separately, often on different footprints	All parameters computed on one identical pixel set, so their agreement is meaningful
Scale and period	Region-wide averages, which can hide individual glaciers	Extends to 2025, covering the decade in which the departure occurs
Negative results	Artefact-driven series usually dropped silently	The spring snow series is reported together with the reason it cannot be interpreted

Crop cultivation in Hopar depends on glacier and snow meltwater (Butz 1989), and the Upper Indus basin as a whole leans heavily on cryospheric storage (Immerzeel et al. 2010). A loss rate about three times the 1990-2015 mean is a change in the supply regime, and Table 3 gives the interval figures in a directly usable form. For melt modelling, debris cover on Bualtar rose from 21.6 % to 29.8 % of the surface between 2015 and 2025; debris thickness governs whether the cover insulates the ice beneath it or enhances melt (Nicholson and Benn 2006; Östrem 1959; Rounce et al. 2021), so a change of that size inside one decade alters the inputs to any distributed melt model applied here. For reproducibility, the full processing chain is a single Google Earth Engine script, every input archive is public, class breaks and

colour specifications are published with this paper (Online Resource 1), and the per-epoch statistics are given in Tables 2 and 3.

This study neither confirms nor refutes the Karakoram Anomaly as a regional phenomenon. One glacier cannot do either. What it provides is a record internally consistent with the anomaly for the period the anomaly was described for, and inconsistent with it afterwards. The same processing chain produces both halves, so the change of behaviour cannot be pinned on a change of method. Regional geodetic records still show near-balance to 2016 and to 2021 (Berthier and Brun 2019; Lhakpa et al. 2022). A departure at one glacier after 2015 therefore shows that individual glaciers can already diverge from that regional mean. Farinotti et al. (2020) consider the anomaly unlikely to persist in the long term under projected warming.

Whether the pattern found here is representative is an open question. If it is, explanations resting on persistent mechanisms, sustained increases in winter precipitation for instance (Archer and Fowler 2004), become harder to hold than explanations in which the anomaly is a temporary balance that enough warming eventually overcomes. Settling the question needs the same corrected processing applied across a population of Karakoram glaciers.

Debris cover and ice loss rise together after 2015. These data alone cannot resolve the direction of causation. Ice loss exposes englacial and subglacial debris, so debris expansion is partly a consequence. Debris also alters the surface energy balance: thin cover lowers albedo and enhances melt, thick cover insulates (Nicholson and Benn 2006; Östrem 1959). Both processes fit the observations here. Separating them needs debris thickness, which optical indices alone do not supply (Rounce et al. 2021). That debris matters for glacier response is now well established (Herreid and Pellicciotti 2020; Scherler et al. 2011).

NDSI cannot see ice beneath debris. Some of what this study records as ice loss may be ice that became debris-covered rather than ice that melted. That the debris class grows by roughly the amount the ice class shrinks between 2015 and 2025 is consistent with either reading. This is an inherent limit of NDSI-based extent mapping and is the strongest argument for pairing it with a thickness-sensitive method.

Limitations

The quantitative results describe 37.08 km², 57.4 % of the 64.56 km² outline. The excluded terrain is not a random sample. It is the terrain cloud obscures most often, so it may run

systematically higher, or more shaded, than the terrain that survived the masking. Scene counts are the second constraint: 12 for 1990 and 15 for 1995, against 90 for 2025. Some pixels in the early epochs carry a single clear observation. The compositing windows are not uniform across the record either, widening from ± 1 to ± 3 years where scenes are scarce, so the early epochs average over a longer period than the late ones.

Debris-covered ice is invisible to NDSI. Ice loss and debris burial cannot be separated by this method. Landsat ST is a radiometric skin temperature and it responds to debris cover (Ahmad and Jasrotia 2026), so part of the LST rise may reflect the debris expansion rather than atmospheric warming; LST and debris are not independent, and the convergence argument weakens to that extent. The snowline figure is a proxy. The 10th percentile of ice-covered elevation is not an equilibrium line altitude, and no mass-balance data were available against which to validate it.

No field validation was possible. No ground control, no mass-balance measurements, no high-resolution imagery, so classification accuracy here is unquantified. Precipitation data are indicative only, because CHIRPS is calibrated on gauges that are sparse and low-lying in this range and under-represents high-altitude snowfall (Funk et al. 2015). Eight epochs is a small sample. Among the interpreted parameters, only the LST trend reaches conventional significance; the other trends are reported with their p-values and should be read as suggestive.

Conclusions

Mean glacier-surface temperature at Bualtar Glacier rose $1.88\text{ }^{\circ}\text{C}$ per decade between 1990 and 2025 ($r^2 = 0.76$, $p = 0.005$). That is the only statistically significant glaciological trend in the study. Ice extent within the comparable footprint fell 7.3 %, from 27.95 to 25.90 km^2 , and most of that decline falls after 2015. Supraglacial debris expanded from 24.8 % to 29.8 % of the glacier surface, with a rise of 8.2 points in 2015-2025 alone. The interval loss rate reached 1.48 % per year in 2020-2025, against 0.20 to 0.92 % per year for every interval from 1990 to 2015.

The record reproduces Karakoram stability for 1990-2015 and departs from it thereafter. Largely independent parameters drawn from four spectral regions agree on the timing of that departure. Two corrections to standard practice changed the results by large margins. Coding change classes jointly rather than by subtraction moved the reported stable fraction for 1990-

1995 from 92.5 % to 74.1 %, and enforcing a common observation footprint removed a spurious doubling of ice area between 1990 and 2000 that satellite coverage had driven. Both formulations are in common use. Both should be checked in comparable studies.

Statements and Declarations

Competing interests. The authors declare no competing interests.

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Author contributions. Zainab Sohail conceived and designed the study, performed the data processing and analysis, produced the cartography and wrote the manuscript. Salman Tariq supervised the work and reviewed and edited the manuscript.

Data availability. All satellite data analysed in this study are publicly available through Google Earth Engine: Landsat Collection 2 Level-2 tier-1 surface reflectance for sensors LT05, LE07, LC08 and LC09, held under Earth Engine collection paths of the form LANDSAT/<sensor>/C02/T1_L2 (U.S. Geological Survey 2020a, 2020b, 2020c), NASADEM (NASA JPL 2020), ERA5-Land (Muñoz-Sabater et al. 2021) and CHIRPS (Funk et al. 2015). Glacier outlines are from the GLIMS database (GLIMS Consortium 2005). Class breaks and colour specifications for every map layer are given in Online Resource 1. The per-epoch statistics file, the Google Earth Engine script, the ArcGIS map documents and all 43 map sheets at 600 dpi generated during this study are available from the corresponding author on reasonable request.

Ethics approval. Not applicable. This study analyses publicly archived satellite imagery and involves no human participants or animals.

Consent to participate. Not applicable.

Consent for publication. Not applicable.

All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

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