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Farinotti, D, Immerzeel, WW, de Kok, RJ et al. (2 more authors) (2020) Manifestations and mechanisms of the Karakoram glacier Anomaly. Nature Geoscience, 13 (1). pp. 8-16. ISSN 1752-0894

https://doi.org/10.1038/s41561-019-0513-5

Manifestations and mechanisms of the Karakoram glacier Anomaly

Daniel Farinotti[1,2] (ORCID: 0000-0003-3417-4570), Walter W. Immerzeel[3] (ORCID: 0000-0002-2010-9543), Remco de Kok[3] (ORCID: 0000-0001-6906-2662), Duncan J. Quincey[4] (ORCID: 0000-0002-7602-7926), Amaury Dehecq[1,2] (ORCID: 0000-0002-5157-1183)

[1]*Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland*

[2]*Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland*

[3]*Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands*

[4]*School of Geography, University of Leeds, Leeds,United Kingdom*

Global-scale glacier shrinkage is one of the most prominent signs of ongoing climatic change. However, important differences in glacier response exist at the regional scale, and evidence has accumulated that one particular region stands out: the Karakoram. In the past two decades, the region has shown balanced to slightly positive glacier budgets, an increase in glacier ice-flow speeds, stable to partially advancing glacier termini, and widespread glacier surge activity. This is in stark contrast to the rest of High Mountain Asia, where glacier retreat and slowdown dominate, and glacier surging is largely absent. Termed the *Karakoram Anomaly*, recent observations show that the anomalous glacier behaviour partially extends to the nearby Western Kun Lun and Pamir. Several complementary explanations have now been presented for explaining the Anomaly's deeper causes, but the understanding is far from being complete. Whether the Anomaly will continue to exist in the coming decades remains unclear, but its long-term persistence seems unlikely in light of the considerable warming anticipated by current projections of future climate.

The Karakoram is the mountain range spanning the borders of Pakistan, India, and China, with extremities reaching into Afghanistan and Tajikistan (Figure 1a). The region is geomorphologically very dynamic[1], with intense interactions between tectonic, fluvial, and mass movement processes. The extremely steep and high topography, characteristic of the region, hosts some of the tallest mountains on Earth, and very dynamic glaciers (Box 1). According to current inventories[2], the region features roughly 13,700 glaciers, covering an area of about 22,800 km^2. The total glacier ice volume is estimated to be in the order of 2,200 km^3, or about 30% of the total for High Mountain Asia[3].

Together with snowmelt, runoff from glaciers is the primary water source for the region's rivers[4], which include tributaries of both the Tarim and the Indus (Figure 1a). This makes the Karakoram's glaciers of utmost importance in supplying water to millions of people downstream[5–7]. Glacier melt has been shown[8] to be of particular importance during periods of drought stress, and hence to contribute to social stability in an otherwise conflict-prone region. Against this background, characterizing the region's glacier evolution is of great relevance.

A peculiar behaviour of Karakoram glaciers was already suspected in early reports[9–12] of 19[th] century explorers. It is difficult to ascertain, however, whether or not the reports were not biased by the perception of an unusually dramatic landscape. Modern observations, instead, are more conclusive, and indeed indicate that – at least for the past decades – Karakoram's glaciers experienced a different evolution when compared to other regions on Earth. The most important difference is the regional glacier mass budget. At the worldwide scale, glaciers outside the Greenland and Antarctic ice sheets have lost an estimated[13] $9{,}625 \pm 7{,}975$ Gt ($1\,\mathrm{Gt} = 10^{12}$ kg) between 1961 and 2016, or $480 \pm 200\,\mathrm{kg\,m^{-2}}$ per year. This is in direct contrast to what is reported for the central parts of the Karakoram, where most recent estimates[14] indicate a mass gain in the order of $120 \pm 140\,\mathrm{kg\,m^{-2}}$ per year. This slight glacier mass gain has likely contributed to an increase in ice flow velocities observable at the regional scale[15].

The frequent occurrence of glacier surges[16] is a second distinguishing characteristic of the Karakoram. Glacier surges are irregular phases of ten- to hundredfold acceleration in glacier flow, typically lasting between a few months to years[17]. Although surges occur in other regions on Earth as well (including Alaska and Svalbard, for example), they are absent for most other parts of High Mountain Asia[18]. In an overview from the 1930s[19], such behaviour was attributed to "accidental changes", and was thought to be responsible for the high number of river-floods caused by the outburst of glacier-dammed lakes. Today, various mechanisms have been proposed to explain glacier surges initiation and clustering (Box 2) but the understanding is far from being complete. Similarly, it remains unclear whether the frequency of Karakoram glacier surges has changed over time, although indications exist[20] that surge-activity might have increased after 1990.

The above peculiarities in glacier behaviour are often referred to as the *Karakoram Anomaly*, a term coined in the mid-2000s (ref. [21]) when indications for anomalous glacier behaviour started to emerge (see Supplementary Section S1 for a brief history on how the idea of a Karakoram Anomaly developed). In the following, we detail the ways in which this Anomaly expresses itself, and review the mechanisms that have been proposed to explain it. We distinguish between early, partially speculative explanations, and more recent, holistic interpretations. We highlight the remaining gaps in the explanation chains, speculate about the Anomaly's implications and future evolution, and suggest avenues for future research.

Manifestations of the Karakoram Anomaly

Slight glacier mass gains and widespread surging activity are the two most prominent features of the Karakoram region. Evidence for the former has accumulated since satellite-based, regional-estimates of glacier surface elevation changes have become available[22–26]. Although patterns of glacier changes are spatially variable (Figure 2), there is now general agreement that the Karakoram experienced balanced glacier budgets, or even marginal glacier mass gains in the early 21$^{\text{th}}$ century[13,14,27]. The most recent studies[14,26,28], however, indicate that the signal of positive glacier budgets is not centred over the Karakoram itself, but rather over its eastern part and the Western Kun Lun (circles in Figure 2; uncertainties shown in Supplementary Fig. S1). The western part of the Karakoram, showing balanced mass budgets, is thus to be understood as a region of transition between negative mass balances in the Pamir and slightly positive mass balances in Western Kun Lun. Interestingly, regional-scale surface-elevation changes neither show significant differences between debris-covered and clean-ice glaciers[22,29] nor between surge-type glaciers and glaciers that do not surge[24].

The slightly positive mass budgets in parts of the Karakoram and Western Kun Lun are also indirectly confirmed by long-term trends in glacier ice-flow velocities (arrows in Figure 2; uncertainties shown in Supplementary Figure S1). Even if glacier-specific velocity changes can be difficult to interpret because of large seasonal and interannual variability[16,30], analyses over the period 2000-2016 show[15,31] velocity changes in the order of 0 to +20% per decade. Regional-wide averages for the Karakoram and the Western Kun Lun are of +3.6±1.2% and +4.0±2.1%

per decade, respectively[15]. This trend in ice flow velocities was shown to be unrelated to the region's surging glaciers[15], and thus interpreted as an indication of increased ice deformation and sliding due to glacier thickening. The thickening is in turn consistent with the positive glacier mass budgets. The findings of accelerating glacier flow are in contrast to what has been observed in other parts of High Mountain Asia, where ice-flow slowdown dominates[15,32].

The dynamic adjustments to positive mass budgets are also manifested in the majority of the region's glaciers showing stable or advancing termini[33,34]. Albeit not resulting in significant net change in glacier area[35], these changes are again in contrast to the rest of High Mountain Asia, where glacier-terminus retreat and area loss largely prevails[36,37]. It must be noted, however, that the detection and interpretation of changes in the region's glacier extents are complicated by the widespread debris-coverage[33]. The debris-covered area itself remained virtually unchanged in the central part of the Karakoram over the last four decades[38], and increased by about 11% over a larger extent and the shorter 2001-2010 period[?]. This further corroborates the balanced (slightly negative) mass budgets reported for the central (eastern) part of the Karakoram[14], given that positive and negative mass budgets would be expected to result in a reduction and an extension of the debris-covered area, respectively.

Many terminus advances and changes in velocity may also be ascribed to glacier surges. The phenomenon is uncommon elsewhere in High Mountain Asia but is widespread in the Karakoram[16] and the nearby regions[31,39,40]. It has been suggested that this clustering of surge-type glaciers might be related to particular climatic and geometric conditions that lead to periodic enthalpy imbalances[18], but the specific controls on surging remain unclear. This is also because data on englacial and subglacial conditions, understood to be pivotal in controlling surge cycles (Box 2), are lacking almost entirely[16]. The frequency of surge events seems to have increased in recent decades[20], potentially correlating with a period of warming atmospheric temperatures[40] and increasing precipitations[20]. No definitive connection between surge activity and changes in external forcing has however been established yet[41], and it is still difficult to discern whether the reported increase in surge frequency is related to a real environmental trend, or to an improved ability to detect surges through advances in observational techniques.

A further open question is for how long the observed anomalous behaviour might have persisted. Early works based on sparse field observations suggest a retreat of the Karakoram glaciers between 1940 and the 1960s (ref. [42]), with periods of slight advances in the late 1970s and 1990s (ref. [43]). Meta-analysis of reports for glacier changes across High Mountain Asia, however, indicates that no significant change occurred since the 1960s[37]. The only field-based mass balance estimate available for the 20th century in the region[44] (Siachen glacier) is negative but very uncertain[45]. Satellite-based estimates, on the other hand, reach back to 1973, and suggest that nearly-balanced glacier budgets might have persisted since then for the Karakoram[46,47], the western Kun Lun[48,49], and the eastern Pamir[50,51]. Also in this case, however, uncertainties are large, and the temporal resolution of such estimates is low – typically only providing information for the period 1973-2000, or for 1973 and later. All of this makes it difficult to establish temporal variations in the Anomaly's magnitude and extent.

Early explanations of anomalous behaviour

Early explanations[52,53] for a potentially-anomalous behaviour of Karakoram glaciers often invoked the substantial debris cover that characterize the glaciers of the region, although it was known that debris covered glaciers were widespread in other parts of High Mountain Asia as well. The debris cover was not only suggested to significantly suppress ice melt in the ablation zones, thus preventing glacier wastage and retreat, but was also suspected[21] to make it difficult to detect glacier changes. The morphology of the glaciers in the Karakoram remained one of the main explanations when the idea of a Karakoram Anomaly was proposed in the mid-2000s: the confinement of the main glacier trunks by characteristically high and steep headwalls (Box 1) was suggested to cause an "elevation effec"[43], i.e. an orographic enhancement of high-altitude precipitation and a related downslope concentration of snowfall driven by avalanches. Combined with an all-year-round accumulation regime, the effect would cause limited sensitivity to warming, since a rise in temperature would only result in a small decrease of the accumulation area.

Indications of a climatic control for the Karakoram's peculiar glacier behaviour emerged in the early 2000s. Archer and Fowler[54,55] analysed 1961-2000 trends in temperature and precipitation for meteorological stations in the region, and identified a significant increases in winter, summer and annual precipitation[54] as well as a lowering of summer mean and minimum temperatures[55]. These observations were independently supported[56,57] by data obtained from tree rings, which indicated that the western Himalaya saw pre-monsoon (March-May) cooling in the latter part of the

20^{th} century[56]. For the Karakoram, the 20^{th} century was even shown[57] to have been the wettest over the past millennium. Combined, the decrease in summer temperatures and increase in precipitation was suggested to be consistent with positive glacier mass balances in the region, an interpretation further supported by the simultaneous decrease in summer river flows[54]. This line of argument was echoed and amplified by a number of subsequent studies[20,22,33,58,59], making it the generally-accepted hypothesis for the Karakoram Anomaly by about 2010.

The deeper causes of the observed temperature and precipitation changes, however, remained elusive. A preliminary analysis[54] identified a significant positive (negative) correlation between winter (summer) precipitation and the North Atlantic Oscillation, whilst later investigations[60] showed that the westerly jet stream over central Asia – a central mechanism for regional moisture transport during winter (Box 3) – had strengthened and shifted to both lower elevations and lower latitudes between 1979 and 2001. These observations remain central to present-day understanding of potential drivers of change (see *Current understanding of the Anomaly's drivers*).

Concerning the widespread occurrence of glacier surges, it was recognized very early that substantial basal sliding must be involved to maintain high rates of glacier flow. Based on a set of observations collected during the 1930s, for example, Finsterwalder[61] suggested that the glaciers of the Nanga Parbat area mainly move through "blockschollen-motion", i.e. sliding-dominated plug-flow, primarily resisted by drag at the glacier margins. The important contribution of basal sliding to the total motion of both surge-type and non-surging glaciers in the Karakoram was confirmed repeatedly through both ground-based[62–66] and remote-sensing observations[67]. Whether and why such high sliding rates are peculiar to the region, however, remains largely unknown.

To explain surge initiation, the literature generally focuses on two main mechanisms, that invoke changes in either thermal or hydrological conditions as the trigger (Box 2). Which of the two is predominant for the Karakoram has been debated[68]. Quincey et al.[59] argued in favour of thermal control, noticing that surges develop over several years and that no seasonality can be discerned in their initiation. In contrast, Copland et al.[20] favoured hydrological control since the active phase of Karakoram surges seems to be short-lived and separated by decades-long phases of quiescence. To explain the increase in surging activity after the 2000s, Hewitt[68] speculated about the role of changes in climate, stating that *"response to climate change seems the only explanation for [the] events at [four tributaries of] Panmah Glacier [Central Karakoram]"*. Demonstrating such a climatic control, however, is difficult, and evidence remains scant.

Current understanding of the Anomaly's drivers

Whilst a climatic control on surging activity is debated, the positive glacier budgets in and around the Karakoram must be associated to the meteorological forcing. Compared to other parts of High Mountain Asia, the latter must either favour more accumulation, less ablation, or a combination of both. Currently, a number of potential explanations are found in the literature, and include increased snowfall in the accumulation zones, or a suite of factors – including increased cloud cover and a higher surface albedo – that reduce the net energy available for the melting of snow and ice.

The Karakoram's general meteorological characteristics are well established[69–71] (Box 3). In winter, when the westerly jet is located south of the Karakoram, mid-latitude cyclones (or *westerlies*) control the region's weather[72,73]. Their associated fronts interact with the extreme topography and can provide heavy mountain precipitation[74]. An increase in strength and frequency of such westerly-dominated precipitation has been identified[75] for the period 1979-2010, and seems to have led to a slight increase in the region's winter snowfall[76]. This is in contrast to other regions in High Mountain Asia, where snowfall trends are mostly negative[69]. The contrasting trends in the geopotential height between different parts of High Mountain Asia (Figure 2 in ref. [76]) have been suggested to be at the origin of the changes in westerlies-driven precipitation events[70,75,76], but the underlying mechanisms are still unclear. The precipitation changes, in turn, have been proposed to exert a strong control on regional glacier mass balances[69,70,77]. It has to be noted, however, that precipitation trends are uncertain and mostly non-significant[78], and that no increase in Karakorams total precipitation is evident in recent meteorological reanalyses (Figure 3b and Supplementary Figure S2b+d).

In summer, the interplay between the monsoon and mid-latitude westerlies is complex, and results in a high inter-annual precipitation variability[69]. This variability has been associated[70,71] to modulations of the *Karakoram / Western Tibetan Vortex*, an atmospheric structure extending from the near surface to almost the tropopause[70]). Temperatures show variability as well, and for the latter part of the 20^{th} century, an increase in diurnal temprature ranges has been inferred from both weather stations [55,79] and tree-rings [56]. This increase has been related to large-scale deforestation, which caused a lowering of the soil's thermal inertia due to reduced water infiltration[56]. A cooling of summer temperatures was observed concomitantly. The cooling was particularly pronounced in the 1960-1980 period[55,79], occurred despite a general warming trend [79], and has been attributed to a weakening of the monsoon[70,71]. It is this summer cooling that has been suggested[55,70] to be a particularly important driver for the balanced glacier budget of the Karakoram in recent decades. It shall be noted, however, that work from tree-ring chronology at one high-elevation site[80] did not provide any indication for Karakoram temperatures being out of phase with other regions in High Mountain Asia over centennial timescales.

Changes in glacier accumulation and ablation have also been suggested[81] to be linked to increased evaporation in Northwest China during the 20th centruy. This increased evaporation – caused by a dramatic increase in irrigation after 1960 (ref. [82]) – has caused a rise in atmospheric moisture, which in turn seems to have resulted in more frequent summer snowfalls in the Western Kun Lun and the Pamir. The increased atmospheric moisture also increased cloudiness and reduced incoming shortwave radiation[81] (Figure 3c), thus reducing ice and snow ablation. This hypothesis is finding support in both observational records and modelling[76,83], but cannot be considered as conclusive yet.

Although often assessed independently, the monsoon-weakening and irrigation hypotheses are in fact inherently interconnected. The weakening of the monsoon has been suggested to be a partial consequence of changes in irrigation itself[84,85]: Increased irrigation causes changes in near-surface heat fluxes, which lead to a cooling of both the surface and the lower troposphere; the troposphere cooling, in turn, decreases the geopotential height over the irrigated regions, thus affecting atmospheric circulation including the westerly jet and the monsoon[84]. Such changes in large-scale circulation would partly explain regional differences in glacier response, and the different glacier budgets in the Karakoram with respect to other regions in High Mountain Asia.

Regional differences in glacier response are also affected by spatial variations in climate sensitivity[86]. The response of glacier mass balance to a given change in temperature, for example, was shown to vary[87], and to correlate well with observed mass budgets itself. These differences can be explained by regional variations in the glaciers' energy balance. Both field-[88,89] and model-based[90] investigations, in fact, indicate that net shortwave radiation is more important in driving glacier melt in the Karakoram than it is in other parts of High Mountain Asia. Since the shortwave radiation budget is decisively controlled by surface albedo and cloudiness, this partly explains why glaciers in the Karakoram might be particularly susceptible to changes in albedo-enhancing summer snowfalls. The increase in summer snowfall and the decrease in net shortwave radiation observed in the Karakoram over the last decades (Figure 3c) might thus have favoured positive glacier budgets, whilst the increases in both temperature and net longwave radiation in other parts of High Mountain Asia (Figure 3a+d) favoured glacier mass loss.

Knowledge gaps, implications, and a look into the future

The Karakoram's balanced to slightly-positive glacier mass budgets are the strongest argument for an anomalous behaviour, both at the scale of High Mountain Asia and globally. Moreover, enough evidence now exists to show that these close-to-balance glacier budgets partially extend to the neighbouring Western Kun Lun and Pamir. When calling for an Anomaly, however, qualitatively different glacier behaviour must be distinguished from regional characteristics. Large, low-elevation and debris-covered glacier termini; strong verticality resulting in pronounced avalanches nourishment; and even the high number of surge-type glaciers might, in fact, rather be considered as a characteristic of the region than an anomaly[91].

Figure 4 provides an overview of the process-chain related to the Anomaly, with a focus on the evolution observed during the past decades. In a nutshell, the interplay between land cover, atmospheric processes, and climate change (Figure 4, point 1) is suggested to have led to summer cooling, increased snowfalls, and reduced net energy available for glacier melt (Figure 4.2). In conjunction with specific glacier properties (Figure 4.3), a combination of these effects resulted in glacier advance, constant to slightly-accelerating glacier ice flow, and insignificant changes in both total glacier area and debris cover (Figure 4.4). This, in turn, reduced downstream flows, and affected glacier-related hazards in some occasions (Figure 4.5). The mechanisms that control the region's glacier peculiar behaviour, including glacier surging for example, are however far from being completely understood. Based on our expert judgement and the reviewed literature, we assigned a relative level of confidence to the degree to which individual elements of Figure 4 are characterized or understood.

The lack of long-term observations, for instance, causes uncertainties in the trend-estimates for factors that drive glacier change. In the Karakoram and nearby regions, this is particularly true for meteorological parameters (Figure 4.2). Air-temperature trends obtained from high-resolution climate models[76], for example, show large differences when compared to climate reanalysis products[92] (Supplementary Figure S2a,c). Precipitation trends show better agreement, although the trends themselves are less certain (Supplementary Figure S2b,d). High-altitude precipitation is particularly poorly quantified, both in terms of temporal and spatial variability, as well as in elevation dependency. Together with the difficulty in characterizing snow transport by wind and avalanches, this makes the estimates of glacier accumulation highly uncertain. The identification of trends is also complicated by the region's high inter-annual climate variability. The latter results in low statistical significance (Supplementary Figure S3) and slow trend emergence, which both complicate attributive studies. The use of climate model ensembles, rather than individual products, can increase the robustness of such studies, but cannot overcome the lack of ground-truth information. This lack decisively affects the level of confidence with which drivers of the Karakoram's glacier budgets can be identified.

The present-day understanding of the mechanisms that control the region's glacier behaviour is often based on model simulations which use simplified parameterisations for representing important glaciological (Figure 4.3) or atmospheric (Figure 4.1) processes[93]. Both introduce uncertainties that are difficult to quantify. The continuous development towards models with higher spatial resolution and complexity is unlikely to resolve this. Whilst some driving processes might be indeed better represented in higher-resolution models, a strong need remains for direct observations that support model calibration and validation. Crucially, such observations need to cover time spans pertinent to glacier changes, and need to be representative in both resolution and spatial coverage. Such observations also hold the key for increasing the understanding of individual processes and process-chains, which in turn is the prerequisite for improving model parametrisations. Bridging the gap between in-situ observations and model simulations remains one of the major challenges when aiming at gaining further insights in the Anomaly's deeper causes.

While surface parameters such as glacier extents, topography, and their temporal evolution (top of Figures 4.3 and 4.4) are observed with increasing accuracy due to advances in remote-sensing techniques, detailed information on subsurface characteristics such as the glaciers' thermal regimes, hydrological systems, and subglacial lithology (Figures 4.3 and 4.4, bottom) remain out of reach. This hampers a robust analysis of the physical processes that control local glacier behaviour. For the Karakoram, this is particularly relevant in the context of the region's surging activity. Advances in the conceptual understanding of surge occurrences are being made[18,94] but a convincing explanation for why surge-type glaciers are clustered in the Karakoram is still missing, and surge behaviour is far from being predictable. Indications that the spatial distribution of surge-type glaciers is importantly controlled by climate now exist[18] but a better characterisation of englacial and subglacial properties would certainly add to the understanding. Better constraining the controls on regional surge activities seem particularly important in light of recent indications that environmental changes may influence catastrophic, surge-like glacier collapses[95,96] (Figure 4.5).

A presently unanswered question is for how long the Anomaly is likely to persist in the future. If the global climate continues to warm as anticipated by current projections[97], it seems unlikely that it will persist in the longer term – especially not in the form of positive glacier budgets[7,98]. Changes in precipitation will affect the future evolution as well. Here, a key uncertainty is how the monsoon system and westerly jet will respond to ongoing warming, and to other forcings including land-use changes. At present, irrigation is suggested to influence the region's climate through the control of heat exchanges and moisture fluxes[84,85]. Irrigated areas, however, cannot continue to expand limitlessly since space is scarce and water resources are limited, and might even shrink if groundwater levels drop beyond economically viable depths. If recent hypotheses on regional-scale mechanisms[81] are accepted, such land-use changes could result in decreased precipitation, possibly affecting the region's glaciers via reduced accumulation.

The anomalous glacier behaviour in the Karakoram and its neighbouring regions is not only a curiosity in an epoch dominated by glacier retreat. The glaciers' importance for regional water supplies[7,8] (Figure 4.5), and the cultural and religious value attributed to glaciers by the local communities and their traditional practices[99] make some of the unanswered scientific questions of great societal relevance. Future glacier evolution, and the effect on both water supplies and glacier related hazards, are of particular concern in this geopolitically complex region where communities have limited resilience to environmental stress. Establishing the mechanisms that are driving the Karakoram Anomaly, their relative importance, and how they are likely to evolve in coming decades, therefore remains a key challenge for climatic and cryospheric researchers alike.

Methods

The trend analyses displayed in Figure 3 are based on the ERA5 climate reanalysis dataset[92]. ERA5 provides global-scale meteorological information at a horizontal resolution of ≈31 km and covering the period 1979 to present. The information stems from an ensemble of ten model members, for which we only consider the ensemble mean (ERA5 standard product). Trends were calculated independently for each grid cell through linear fitting of the accumulated annual or summer values.

Data availability: The data shown in the individual Figures are available through the original publications (cited).

Code availability: The code used to produce Figures 2 and 3 is available upon request.

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Correspondence and requests for materials should be addressed to D.F.

Acknowledgements We thank Fanny Brun for providing the data underlying Figure 2 and Supplementary Figure S1, and Jesse Norris for providing the data for Supplementary Figure S3.

Author contributions DF initiated the article, designed the figures and led the writing, to which all authors contributed. WWI and DQ provided materials for Figure 1 and Box 1. AD provided materials for Figures 1 and 2. The analyses shown in Figure 3 and Supplementary Figures S2 and S3 were performed by RdK. RdK and WWI conceived Figure 4, with additions from AD, DF, and DQ.

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Competing financial interests The authors declare no competing financial interests.

Box 1 – Peculiarities of Karakoram glaciers Compared to other regions of High Mountain Asia, glaciers in the Karakoram are unusually large[2], and have exceptional elevation ranges. The extremely high altitudes, reaching above 8,000 m a.s.l. at times, cause precipitation to occur as snow during most of the year, giving rise to a *year-round accumulation regime*[43]. The characteristic, steep mountain walls confining the accumulation area of many glaciers cause orographic concentration of snow (*Turkestan-* and *Mustagh-type* glaciers[43]) and are source of extensive debris[1]. The latter covers the ablation zones of many glaciers in the region. The debris cover, in turn, makes the glacier response to external forcing non-linear[100], and results in large glacier portions persisting at lower elevations when compared to debris-free glaciers responding to the same climate forcing[101]. Widespread surging activity gives rise to some peculiar geomorphic features, such as lobed medial moraines, strandlines, ice foliation, and rugged, strongly-crevassed glacier surfaces[20].

<u>BOX 2</u> – Classical surging mechanisms Two main mechanisms have been proposed to explain glacier surging[102]: *thermal* and *hydrological* control. Both attribute the ultimate cause of the acceleration in ice motion to an increase in subglacial water pressure and the resulting enhancement of sliding at the glacier base.

- In *thermally controlled surges*, changes in basal temperature promote a positive feedback between ice deformation, basal melt, pore water pressure, and sliding. This mechanism is comparatively slow, and leads to seasonally independent surge initiation- and termination-phases that are several years long.
- In *hydrologically controlled surges*, the increase in sliding velocities are directly caused by a change in the efficiency, and therefore water pressure, of the subglacial drainage system. This mechanism is much faster than the thermal one, and results in phases of winter initiation and summer termination, both of days to weeks duration.

Recent work[94] proposed a unifying theory that recognises the importance of both heat and water, casting surges as an imbalance in enthalpy. This imbalance occurs only within narrow climatic and geometric envelopes[18], both of which can be found in the Karakoram and neighbouring regions.

<u>BOX 3</u> – Karakoram climate In contrast to the neighbouring Himalaya, which are under the influence of the Indian monsoon, the Karakoram's climate[54] is predominantly influenced by westerly weather systems and the Tibetan anticyclone. Most of the annual precipitation falls in spring and winter, during which the westerly influence dominates (Fig. 1b). The Mediterranean and the Caspian Sea are the main moisture sources during such conditions. The monsoon makes sporadic incursions during summer, with amounts of precipitation rapidly decreasing from south-east to north-west. Moisture from the Arabian Sea is brought to the region when low-pressure systems develop over Pakistan. In such cases, precipitation decreases sharply northward due to orographic shielding.

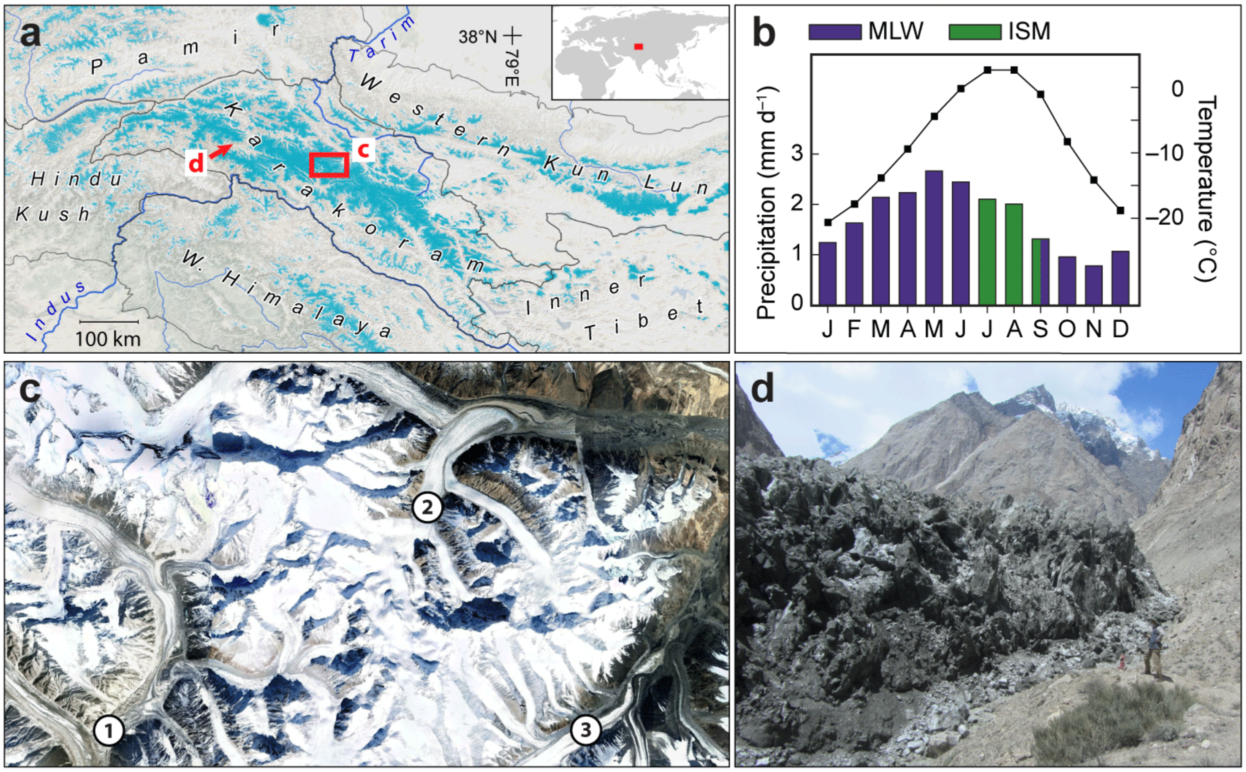

Figure 1: **Distribution of Karakoram glaciers and climate characteristic.** **a** Glacier coverage and regions as per Randolph Glacier Inventory[2] version 6. **b** Regional average temperature (connected squares) and precipitation (bars) for the period 1989-2007, re-drawn from ref. [103]. The influence of Mid-Latitude Westerlies (MLW) and the Indian Summer Monsoon (ISM) is shown based on the classification by ref. [90]. **c** GoogleEarth image with looped and folded moraines providing indications of past surges at (1) Panmah, (2) South Skamri, and (3) Sarpo Langgo Glacier. **d** Terminus of Shishper Glacier in May 2019, showing clear sign of recent advance (image credit: Rina Seed). Note the person for scale.

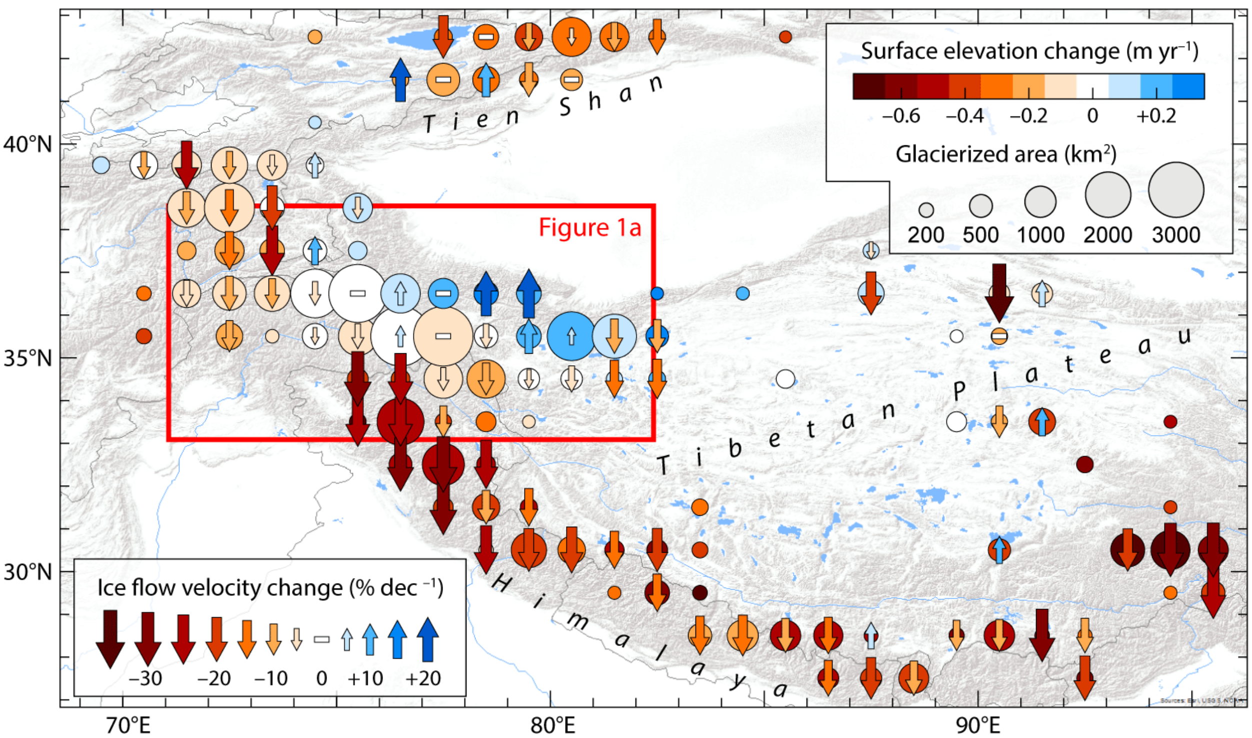

Figure 2: **Recent glacier changes in High Mountain Asia.** The rate of glacier surface elevation change[28] is shown together with changes in ice flow velocity[15] for the period 2000-2016. The size of the circles is proportional to the glacier area. Data are aggregated on a $1^\circ \times 1^\circ$ grid, and uncertainties are shown in Supplementary Figure S1. The red box indicates the area shown in Figure 1a and includes the Karakoram.

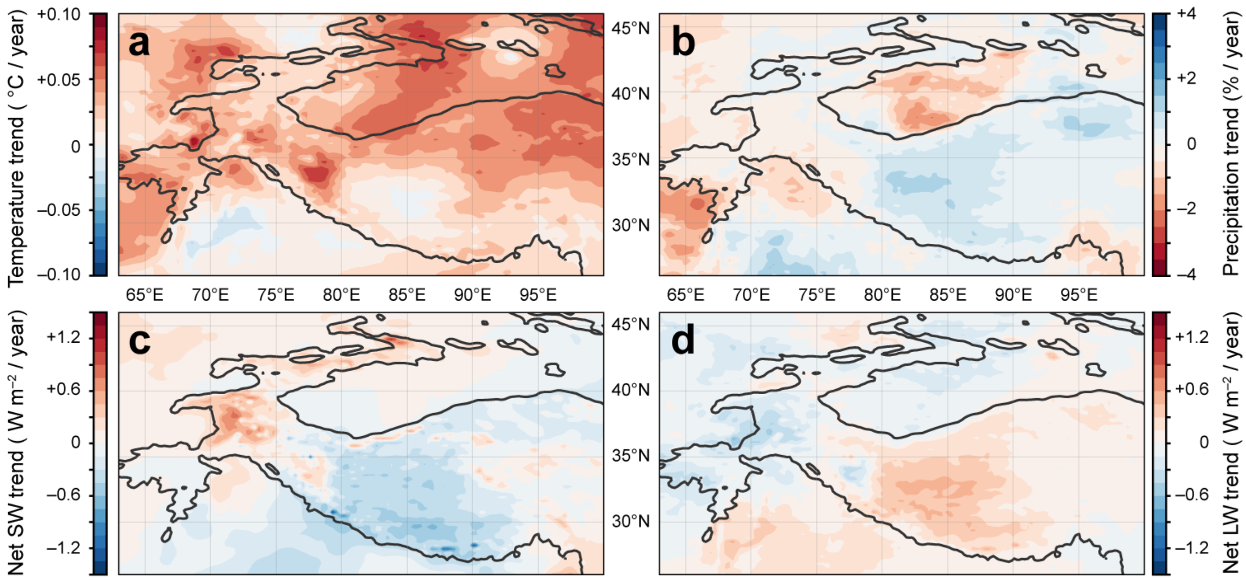

Figure 3: **Potential meteo-climatic drivers of the Karakoram Anomaly.** The spatial distribution of linear trends in (**a**) summer (JJA) temperature, (**b**) annual precipitation, (**c**) summer net shortwave (SW) radiation, and (**d**) summer net longwave (LW) radiation is shown for the time period 1980-2018. The representations are based on ERA5 data[92]. Trend significances and a comparison to the high-resolution climate model results by ref. [76] are provided in Supplementary Figures S3 and S2, respectively. A 2,000 m contour line (black) is provided for orientation.

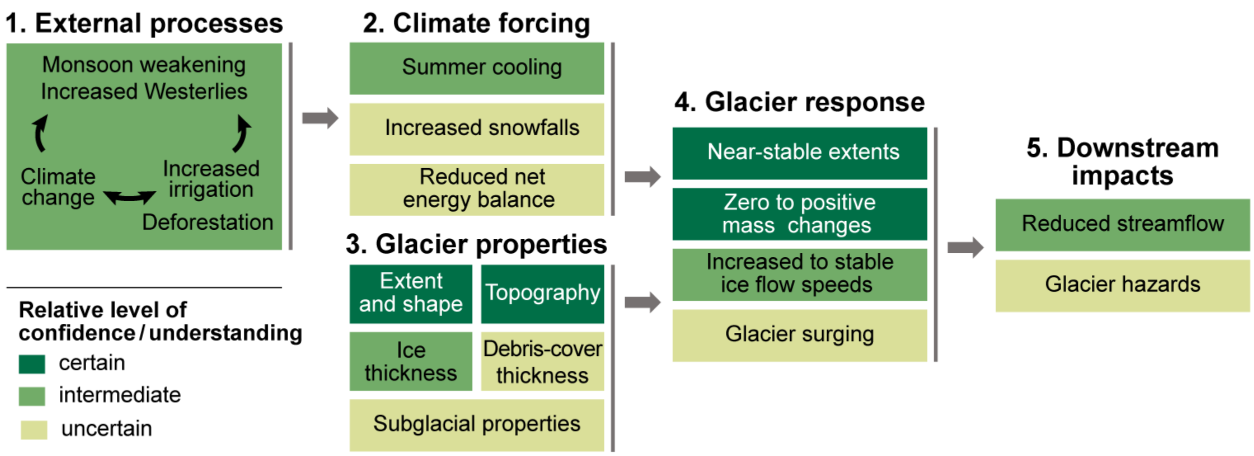

Figure 4: **Schematic of the process-chain leading to anomalous glacier evolution.** For every element, a relative level of confidence in its characterization or understanding is given. The confidence level is based upon the authors' expert judgement and literature review.