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A Weighted Meta-Analysis of Himalayan and Karakoram Glacier Mass Balance and Area Change: Heterogeneity Decomposition, the Karakoram Anomaly and the Method Effect

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ABSTRACT: Published estimates of glacier change in the Himalaya and Karakoram are usually compared as unweighted means or by narrative contrast, so the size of the regional differences and the share of disagreement that reflects real spatial variability rather than measurement noise remain unquantified. Here we apply a formal random-effects meta-analysis to published estimates of specific mass balance (k = 56 estimates from 21 source publications, observation periods spanning 1966 to 2019) and glacier area change (k = 16 estimates from 10 publications). Models were fitted by restricted maximum likelihood with source publication as a clustering level, and heterogeneity was decomposed with Cochran's Q, I2 and meta-regression on sub-region, period midpoint, method, spatial scale and period length. The pooled Himalaya-Karakoram mass balance was -0.28 m w.e. a−1 (95% CI -0.37 to -0.19), with high heterogeneity (I2 = 83%). The Karakoram pooled to -0.06 m w.e. a−1 (-0.10 to -0.02) with no detectable heterogeneity, and differed from the Himalayan mean by +0.34 m w.e. a−1 over matched post-2000 periods (p < 0.001), a difference that survived every sensitivity analysis. Sub-region alone explained about three quarters of the between-estimate variance. Contrary to expectation, the between-study comparison found no significant shift after 2000 in the Himalaya (-0.07 m w.e. a−1, p = 0.31), although within-study pre/post comparisons pointed the same way (-0.14 m w.e. a−1, p = 0.06), indicating that between-study heterogeneity is large enough to mask a real but modest acceleration. Glaciological estimates were more negative than geodetic estimates in the crude comparison (-0.31 m w.e. a−1, p = 0.026), but the difference disappeared once spatial scale was controlled (+0.04 m w.e. a−1 at glacier scale, p = 0.87), which suggests that the well-known negative bias of in situ series is a selection effect of small, low-lying monitored glaciers rather than a method artefact. Area change pooled to -0.32 % a−1 but with extreme heterogeneity (I2 = 98%) and strong small-study asymmetry, so weighted synthesis of this outcome is not yet robust. The results provide the first weighted regional baselines for the Himalaya and Karakoram and show that reporting of uncertainty, not the number of studies, is now the limiting factor for synthesis.

1. INTRODUCTION

Glaciers of the Himalaya and Karakoram feed the Indus, Ganges and Brahmaputra and buffer dry-season runoff for several hundred million people (Immerzeel et al., 2020). Their recent behaviour has been described by a large number of studies using in situ glaciological measurements, differencing of digital elevation models (DEMs), satellite laser altimetry and, more recently, regional modelling. Reviews of this literature agree on the broad picture: most of the Himalaya has been losing mass since at least the 1970s, the rate of loss appears to have increased after about 2000, and the Karakoram has been close to balance, a pattern first described by Hewitt (2005) and now referred to as the Karakoram anomaly (Bolch et al., 2012; Azam et al., 2018; Farinotti et al., 2020).

What the reviews have not done is quantify these statements. Bolch et al. (2012) compiled published mass balances and area changes in supplementary tables and compared them by inspection. Azam et al. (2018) computed arithmetic means of glaciological series and of geodetic estimates, and showed that the two agree better once likely flawed series are removed, but the comparison was unweighted and no test was reported. Bolch et al. (2019) tabulated per-region averages across all study types, again without weights or uncertainties. Cogley (2011) produced interpolated pentadal averages from the in situ record. Kääb et al. (2015) contrasted contending regional estimates for 2003 to 2008 but did not pool them. In each case the reader is left with a list of numbers and a narrative judgement about which ones agree.

This matters for three reasons. First, published estimates carry very different uncertainties, from about ±0.03 m w.e. a^{-1} for a multi-thousand-square-kilometre DEM difference to ±0.4 m w.e. a^{-1} for an in situ series on a single glacier. An unweighted mean gives a single-glacier series with a large error the same influence as a region-wide estimate. Second, the estimates disagree far more than their stated uncertainties allow, and it is not known how much of that disagreement is real spatial and temporal variability and how much reflects method, scale or period. Third, two long-standing claims in the literature, that the Karakoram differs significantly from the Himalaya and that glaciological series are biased negative relative to geodetic ones, have never been tested formally against the uncertainties of the estimates themselves.

Meta-analysis was developed precisely for this situation (Gurevitch et al., 2018). A random-effects model weights each estimate by the inverse of its variance plus a between-estimate variance component, gives a pooled value with a confidence interval, and returns Cochran's Q and I^2 as measures of how much of the dispersion exceeds sampling error (Higgins and Thompson, 2002). Meta-regression then asks how much of that excess is explained by moderators such as region, period and method (Viechtbauer, 2010). Multilevel extensions handle the fact that one paper often contributes several estimates (Van den Noortgate et al., 2013; Nakagawa and Santos, 2012). These tools are standard in ecology and medicine but have not, to our knowledge, been applied to Himalaya-Karakoram glacier change.

Here we do so. We assemble published estimates of specific mass balance and area change with their stated uncertainties, sources and observation periods, fit random-effects and three-level models by restricted maximum likelihood (REML), decompose heterogeneity, and test three hypotheses that summarise the current narrative:

H1. Mass loss in the Himalaya has been more negative after 2000 than before.

H2. The Karakoram differs significantly from the Himalayan mean over matched periods.

H3. Glaciological estimates are systematically more negative than geodetic estimates for the same region and period, as expected if monitored glaciers are a biased sample.

We also report sensitivity analyses that drop series flagged as unreliable in their source studies, drop values taken from compilation tables rather than primary papers, and reinterpret the stated uncertainties, and we test for small-study effects. The aim is not to replace the regional geodetic syntheses of Brun et al. (2017), Shean et al. (2020) or Hugonnet et al. (2021), which measure change directly over near-complete glacier samples, but to provide a formal account of what the accumulated published record says, how consistent it is, and where its disagreements come from.

2. DATA AND METHODS

2.1 Scope and design

The synthesis covers glaciers of the Karakoram and the western, central and eastern Himalaya. Two outcomes were defined in advance. Outcome 1 is the specific (glacier-wide, area-averaged) mass balance in metres of water equivalent per year (m w.e. a^{-1}). Outcome 2 is the rate of glacier area change in per cent per year (% a^{-1}). Moderators were sub-region (Karakoram, western Himalaya, central Himalaya, eastern Himalaya, with a fifth category for estimates spanning the whole Himalayan arc), method (glaciological, geodetic DEM differencing, satellite altimetry; no modelled estimate with a stated uncertainty was found within scope), observation period midpoint, period length and spatial scale (single glacier, basin or catchment, sub-region, region). The hypotheses, models and sensitivity analyses were fixed before extraction began.

Sub-regions follow the scheme used by Bolch et al. (2012, 2019) and Azam et al. (2018). Jammu and Kashmir, Ladakh, Himachal Pradesh (including Lahaul-Spiti) and Uttarakhand (Garhwal) were coded western Himalaya; Nepal, including the Everest and Langtang areas, together with the Tibetan slope of the central Himalaya, were coded central Himalaya; Sikkim, Bhutan and Arunachal Pradesh were coded eastern Himalaya. The Hindu Kush, Pamir, Kunlun, Nyainqentanglha and interior Tibetan estimates that many of the source papers also report were recorded but excluded from all analyses, as were High Mountain Asia totals.

2.2 Literature harvest and extraction

The estimate set was assembled in two stages. First, the compilation tables of Bolch et al. (2012, Supplementary Tables S5 and S6), Bolch et al. (2019, Table 7.3) and the review of Azam et al. (2018) were used to identify primary studies and to obtain values from primary papers that were not accessible in full text. Second, the regional geodetic and altimetry syntheses published since 2012 were read directly: Kääb et al. (2012, 2015), Gardelle et al. (2013), Brun et al. (2017), Maurer et al. (2016, 2019), King et al. (2019), Shean et al. (2020), Bhattacharya et al. (2021) and Hugonnet et al. (2021), together with the Karakoram-specific studies of Rankl and Braun (2016), Bolch et al. (2017), Lin et al. (2017), Zhou et al. (2017) and Berthier and Brun (2019), the glacier- and basin-scale geodetic studies of Bolch et al. (2011), Nuimura et al. (2012), Fujita and Nuimura (2011) and Vincent et al. (2013), and the in situ series of Azam et al. (2016), Sherpa et al. (2017), Mandal et al. (2020) and Stumm et al. (2021). Area-change studies were harvested from the same compilations and from the basin-scale inventories of Bolch et al. (2008), Bhambri et al. (2011, 2013), Racoviteanu et al. (2015), Thakuri et al. (2014), Ojha et al. (2016), Bajracharya et al. (2014), Minora et al. (2016), Mir et al. (2017) and Bahuguna et al. (2014). Reference lists of all of these were screened for further region- or basin-scale estimates.

Every value was recorded exactly as printed, with its uncertainty as printed, the observation period, the method, the spatial unit and a verbatim quotation or table reference so that it can be checked against the source. Nothing was imputed: where a paper printed a value without an uncertainty, the value was recorded but excluded from the weighted models; where a paper printed a range rather than a value, it was excluded. Values taken from a compilation table rather than read in the primary paper are labelled as obtained via the compilation with the primary study cited, a practice that is acceptable when disclosed (Gurevitch et al., 2018), and are tested separately in the sensitivity analyses. Elevation-change rates that were not converted to water equivalent by the source (Kääb et al., 2015) were excluded because no density assumption was made on the authors' behalf. The only arithmetic performed on published numbers was to divide a printed total area change over a printed period by the period length to obtain a rate, and in one case (Minora et al., 2016) to express a printed change in km^2 as a percentage of the printed initial area. Both operations are noted in the coding sheet.

2.3 Selection of the analytical set

Many papers report nested or overlapping estimates. To avoid counting the same glaciers and years more than once, the following rules were applied before analysis. Where a study reported a full period and sub-periods that partition it, the sub-periods were used and the full period was dropped. Where a sub-period did not partition the full period, the full period was used. Where a study reported an aggregate and its non-overlapping spatial parts, the parts were used. Subsets defined by glacier type (surge-type, debris-covered, lake-terminating, size class) were excluded in favour of the all-glacier estimate, except for Rankl and Braun (2016), whose two type-based groups together make up the sample and were both retained. Glacier-by-glacier values that sit inside a reported basin aggregate (for example the ten Khumbu glaciers of Bolch et al., 2011) were excluded in favour of the aggregate. Where later work superseded an earlier estimate from the same data (Gardelle et al., 2012 reprocessed in Gardelle et al., 2013; Wagnon et al., 2013 extended by Sherpa et al., 2017; Azam et al., 2012 and 2016 extended by Mandal et al., 2020) the later estimate was used. All excluded rows remain in the coding sheet with the reason for exclusion.

The resulting analytical set for Outcome 1 contains 56 estimates from 21 source publications: 43 geodetic, 6 altimetry and 7 glaciological; 15 at glacier scale, 11 at basin scale, 25 at sub-region scale and 5 at the scale of the whole Himalayan arc; 13 in the Karakoram, 6 in the western, 28 in the central and 4 in the eastern Himalaya, and 5 arc-wide. Observation periods run from 1966 to 2019 with a median length of 12 years; 16 estimates have a period midpoint before 2000 and 40 after. Ten values were obtained via a compilation table. For Outcome 2 the analytical set contains 16 estimates from 10 publications with a printed uncertainty. A further 20 glaciological series and 25 basin-scale area-change rates without printed uncertainties, together with the unweighted compilation means of Bolch et al. (2019), were retained for the unweighted comparison in Section 3.6.

2.4 Statistical models

Published uncertainties were treated as one standard error. This is the convention stated explicitly by Gardelle et al. (2013) and Kääb et al. (2015) and is the usual practice in the geodetic literature, but several sources do not state the confidence level of their ± values, so the assumption is tested in Section 3.5 by halving all uncertainties. For each estimate i the sampling variance was $v_i = SE_i^2$.

The primary model is a three-level random-effects model, $y_{ij} = \mu + u_j + e_{ij} + \varepsilon_{ij}$, where j indexes the source publication, u_j is a between-source random effect, e_{ij} a within-source between-estimate effect and ε_{ij} the sampling error with known variance v_{ij} (Van den Noortgate et al., 2013). Variance components were estimated by REML (Viechtbauer, 2010). The conventional two-level model was fitted alongside for comparison. Heterogeneity was summarised by Cochran's Q with its chi-square test, by I^2 computed from the total between-estimate variance and the typical sampling variance of Higgins and Thompson (2002), and by a 95% prediction interval for a new estimate (IntHout et al., 2016). Confidence intervals and p-values for pooled values and regression coefficients are reported with the Knapp and Hartung (2003) small-sample adjustment; unadjusted Wald values were also computed and led to the same conclusions in every case.

Next, we fitted mixed-effects meta-regressions. H1 was tested in the Himalayan estimates (western, central, eastern and arc-wide) with an indicator for period midpoint after 2000, with the midpoint as a continuous covariate, and with adjustment for method and scale. Because between-study heterogeneity can mask a temporal change that individual studies detect, H1 was also tested on within-study differences: for each source that reported a pre-2000 and a post-2000 estimate for the same glaciers, the difference was computed with its variance as the sum of the two variances and pooled. H2 was tested with an indicator for the Karakoram in all sub-regional estimates adjusted for midpoint, in the post-2000 estimates alone, in estimates whose periods fall entirely within the common satellite window 1999 to 2016, and with adjustment for method and scale. A region by era interaction was tested by a joint Wald test. H3 was tested with an indicator for glaciological method in the geodetic and glaciological estimates, first crude, then adjusted for sub-region and midpoint, then restricted to glacier-scale estimates so that in situ series are compared only with geodetic values for single glaciers, and finally on matched pairs of glaciological and geodetic values for the same glacier over the same or overlapping years. A full model of record with all moderators was fitted to the sub-regional set and the proportion of between-estimate variance explained was computed as the relative reduction in the total between-estimate variance.

Sensitivity analyses repeated the main models after dropping estimates flagged as unreliable in the source (the Bhutan altimetry value of Kääb et al., 2012, for which Gardelle et al., 2013 note insufficient ICESat coverage), after dropping values obtained via a compilation, after halving all published uncertainties, and by leaving out one source publication at a time. Small-study effects were examined with a funnel plot and Egger's regression of the estimate on its standard error (Egger et al., 1997). The same models were fitted to Outcome 2 with an additional analysis dropping the source whose stated uncertainties were an order of magnitude smaller than the rest. All models were implemented in Python 3 with NumPy and SciPy; the coding sheet and scripts are supplied as supplementary material.

3. RESULTS

3.1 Pooled mass balance and heterogeneity

Figure 1 shows the 56 estimates by sub-region with their published uncertainties. The three-level model gave a pooled Himalaya-Karakoram mass balance of -0.28 m w.e. a^{-1} (95% CI -0.37 to -0.19), and the two-level model gave the same central value with a narrower interval (-0.34 to -0.21), indicating that clustering within source publications matters for the precision but not the location of the pooled value. Heterogeneity was high: Q = 257.4 on 55 degrees of freedom ($p < 0.001$), $I^2 = 83\%$, and the between-estimate standard deviation was 0.20 m w.e. a^{-1}. The 95% prediction interval, -0.70 to 0.14 m w.e. a^{-1}, spans balance, which means that a new region- or glacier-scale estimate anywhere in the range could not be called surprising. The inverse-variance fixed-effect value, -0.21 m w.e. a^{-1}, is less negative than the random-effects value because it is dominated by the very precise Karakoram estimates, while the unweighted mean, -0.31 m w.e. a^{-1}, is more negative because it gives equal weight to the small-glacier in situ series.

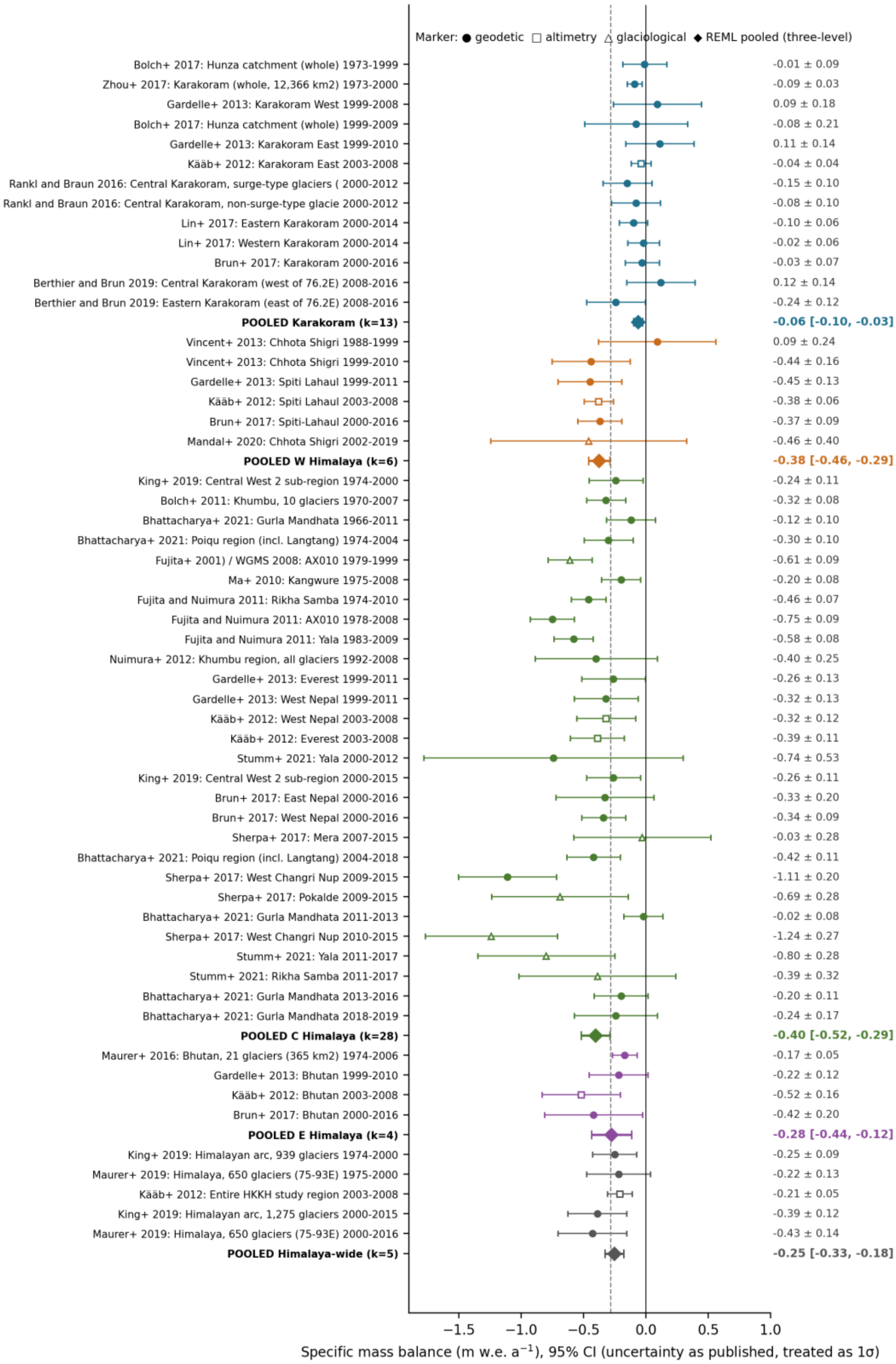

Figure 1. Forest plot of published specific mass balance estimates for the Karakoram and the western, central and eastern Himalaya, with arc-wide estimates. Bars are 95% intervals from the published uncertainty treated as one standard error. Diamonds are REML three-level pooled values by sub-region. The dashed line is the overall pooled value.

3.2 Sub-regional structure

Pooling within sub-regions (Table 1) separated a near-balanced Karakoram from a consistently negative Himalaya. The Karakoram pooled to -0.06 m w.e. a^{-1} (-0.10 to -0.02) from 13 estimates with Q = 9.5 on 12 degrees of freedom ($p = 0.66$) and $I^2 = 0\%$, which suggests that the Karakoram estimates, from seven independent groups using Hexagon, SRTM, ASTER, SPOT, TanDEM-X and ICESat data over periods from 1973 to 2016, are mutually consistent within their stated errors. The western Himalaya pooled to -0.38 m w.e. a^{-1} (-0.49 to -0.26), also without detectable heterogeneity, although from only 6 estimates. The central Himalaya pooled to -0.40 m w.e. a^{-1} (-0.53 to -0.28) with $I^2 = 73\%$, reflecting the wide spread of glacier-scale values in the Everest and Langtang areas. The eastern Himalaya pooled to -0.28 m w.e. a^{-1} (-0.54 to -0.02) from 4 estimates, and the arc-wide estimates to -0.25 m w.e. a^{-1} (-0.36 to -0.15).

In the full meta-regression (Table 3), sub-region alone accounted for most of the explained variance and the model with all moderators reduced the total between-estimate variance by 75%, with the residual I^2 falling from 83% to 51%. Relative to the Karakoram, the western, central and eastern Himalaya were -0.27, -0.26 and -0.24 m w.e. a^{-1} more negative respectively (all $p < 0.02$). Period midpoint, period length and method were not significant once region and scale were in the model; glacier-scale estimates were -0.20 m w.e. a^{-1} more negative than sub-regional estimates ($p = 0.023$).

3.3 H1: change after 2000

Across the Himalayan estimates the post-2000 indicator was -0.07 m w.e. a^{-1} (95% CI -0.20 to 0.06, $p = 0.31$) and the continuous midpoint coefficient was -0.04 m w.e. a^{-1} per decade ($p = 0.25$). Adjusting for method and scale moved the indicator to -0.09 m w.e. a^{-1} ($p = 0.17$). Restricting to geodetic estimates gave -0.08 m w.e. a^{-1} ($p = 0.23$), and dropping the values obtained via compilations gave -0.11 m w.e. a^{-1} ($p = 0.14$). The direction is consistently towards more negative balances after 2000, but the between-study comparison does not reach significance at any conventional level. Within the Karakoram the indicator was +0.03 m w.e. a^{-1} ($p = 0.43$), and the joint test of the region by era interaction was not significant (Wald $\chi^2 = 5.0$ on 3 degrees of freedom, $p = 0.17$).

The within-study comparison told a clearer story. Six sources reported pre- and post-2000 estimates for the same glaciers: Maurer et al. (2019) and King et al. (2019) for the Himalayan arc, King et al. (2019) for their Central West 2 sub-region, Bhattacharya et al. (2021) for the Poiqu region, Vincent et al. (2013) for Chhota Shigri and Bolch et al. (2017) for the Hunza catchment. Every difference was negative. The pooled within-study change was -0.14 m w.e. a^{-1} (95% CI -0.29 to 0.01, Wald $p = 0.059$, Knapp-Hartung $p = 0.13$) with $I^2 = 0\%$. Within the post-2000 estimates themselves there was no trend with midpoint (-0.10 m w.e. a^{-1} per decade, $p = 0.55$). Taken together, these results indicate that a modest acceleration of Himalayan mass loss after 2000, of the order of 0.1 to 0.15 m w.e. a^{-1}, is present when the same glaciers are compared across periods, but that it is smaller than the between-study spread and is therefore not recoverable from a comparison of independent estimates.

3.4 H2: the Karakoram anomaly

The Karakoram indicator was large, precise and stable across specifications (Table 2). Over matched post-2000 periods (11 Karakoram and 26 Himalayan estimates) the Karakoram was +0.34 m w.e. a^{-1} less negative than the Himalayan mean (95% CI 0.24 to 0.45, $p < 0.001$), the Himalayan intercept being -0.40 m w.e. a^{-1}. Restricting to estimates whose periods lie entirely within 1999 to 2016 (11 versus 21) gave +0.34 m w.e. a^{-1} ($p < 0.001$). Across all sub-regional estimates with adjustment for midpoint the difference was +0.34 m w.e. a^{-1} ($p < 0.001$). Adjustment for method and scale reduced it to +0.26 m w.e. a^{-1} ($p < 0.001$) because the Karakoram set contains no glacier-scale in situ series. Before 2000 only two Karakoram estimates exist (Zhou et al., 2017; Bolch et al., 2017), and the difference was +0.27 m w.e. a^{-1} ($p = 0.10$), the same size but with a wide interval. The difference was unchanged when the flagged Bhutan value was dropped (+0.34), when compilation-derived values were dropped (+0.35) and under the two-level model (+0.31). H2 is therefore supported without qualification: the published record places the Karakoram about a third of a metre of water equivalent per year above the Himalaya, and the Karakoram estimates themselves are homogeneous.

3.5 H3: glaciological versus geodetic estimates

The crude comparison reproduced the pattern reported by Azam et al. (2018): the 7 glaciological series pooled to -0.62 m w.e. a^{-1} against -0.25 m w.e. a^{-1} for the 43 geodetic estimates, a difference of -0.31 m w.e. a^{-1} (95% CI -0.57 to -0.05, $p = 0.026$). Adjusting for sub-region and period midpoint reduced the difference to -0.21 m w.e. a^{-1} ($p = 0.08$). When the comparison was restricted to glacier-scale estimates, so that in situ series on single glaciers were compared with geodetic balances of single glaciers (7 versus 8), the difference vanished: +0.04 m w.e. a^{-1} (95% CI -0.38 to 0.45, p = 0.87). The four matched pairs for the same glacier and overlapping years (Chhota Shigri, West Changri Nup, AX010 and Yala) gave a pooled glaciological minus geodetic difference of +0.08 m w.e. a^{-1} (-0.14 to 0.30) with $I^2 = 0\%$. Among post-2000 estimates, glacier scale was associated with -0.53 m w.e. a^{-1} ($p < 0.01$) while method was not (+0.10 m w.e. a^{-1}, p = 0.63).

The pattern is clear. Glaciological estimates are more negative than the regional geodetic record, but geodetic estimates for the same small glaciers are equally negative. The negative offset of the in situ record is therefore a property of which glaciers are monitored, small, accessible, mostly debris-free and low-lying, and not of how they are measured. H3 as a claim about method bias is not supported; H3 as a claim about sample selection is.

3.6 Sensitivity, small-study effects and comparison with unweighted synthesis

Table 4 lists the sensitivity results. Dropping the flagged Bhutan altimetry value, dropping the ten compilation-derived values, and halving all published uncertainties changed the pooled value by at most 0.04 m w.e. a^{-1}. Leaving out one source at a time moved it between -0.29 and -0.25 m w.e. a^{-1}; the largest single influence came from Sherpa et al. (2017), whose Everest-region series are the most negative in the set. Halving the uncertainties raised I^2 to 97%, indicating that if published ± values are two-sigma the estimates disagree even more than the main analysis implies. Egger's test showed no significant funnel asymmetry for mass balance (intercept -0.077, p = 0.11; Figure 3), and the same held for the geodetic estimates alone (p = 0.16).

The weighted results differ from earlier unweighted summaries in an informative way. Azam et al. (2018) reported an unweighted mean of −0.59 m w.e. a^{-1} for 24 glaciological series and −0.49 m w.e. a^{-1} for 20 screened series; the 20 glaciological series in our coding sheet, with and without uncertainties, average -0.55 m w.e. a^{-1}, and the seven with uncertainties average -0.60 m w.e. a^{-1}, so the in situ record has not changed. The weighted regional values are, however, much less negative than these means and much closer to the compilation averages of Bolch et al. (2019) for about 2000 to 2010 (Karakoram −0.06, western Himalaya −0.50, central Himalaya −0.42, eastern Himalaya −0.66 m w.e. a^{-1}), with the exception of the eastern Himalaya, where the weighted value (-0.28) is pulled towards the long precise Bhutan estimate of Maurer et al. (2016). Weighting therefore matters most where a few precise multi-decadal estimates coexist with many short, uncertain ones.

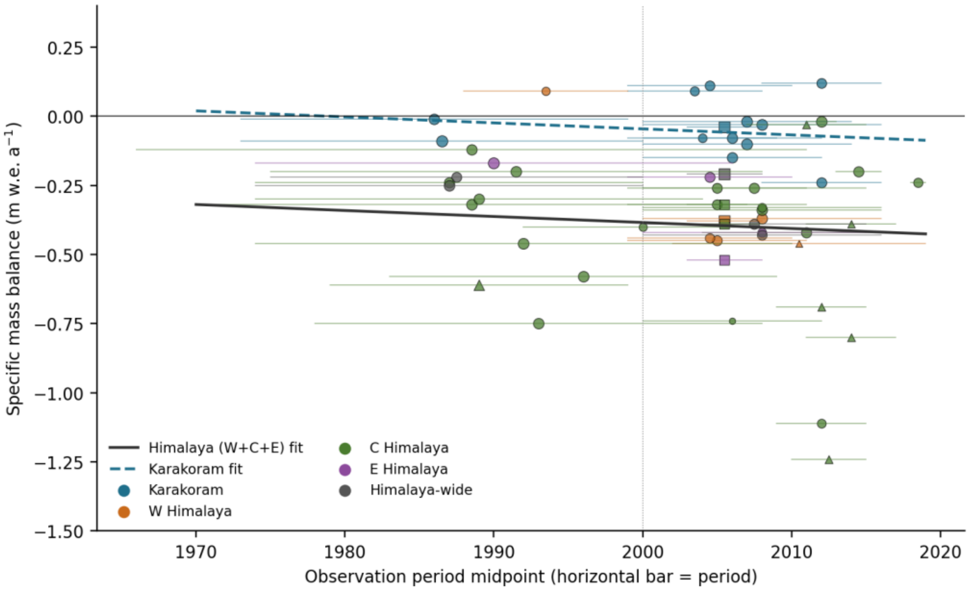

Figure 2. Specific mass balance against observation period midpoint. Symbol size is proportional to random-effects weight; horizontal bars show the observation period; circles are geodetic, squares altimetry, triangles glaciological. Lines are the fitted Himalaya (solid) and Karakoram (dashed) values from the meta-regression with midpoint as covariate.

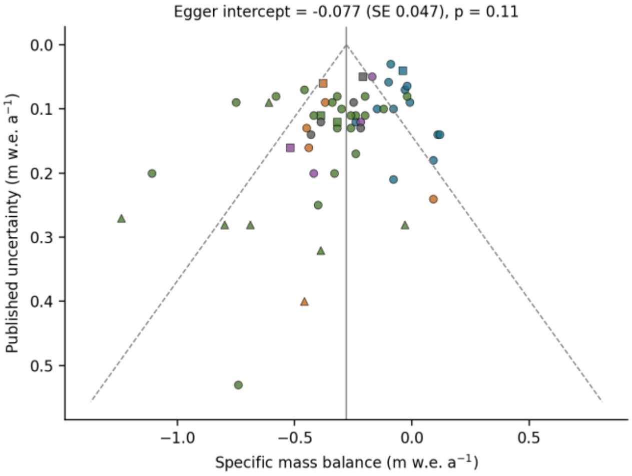

Figure 3. Funnel plot of mass balance estimates against published uncertainty. Dashed lines are the pseudo 95% limits around the two-level pooled value.

3.7 Outcome 2: area change

Sixteen area-change estimates from ten publications carried a printed uncertainty (Figure 4, Table 5). The three-level pooled rate was -0.32 % a^{-1} (95% CI -0.52 to -0.13) with I^2 = 98%. The Karakoram pooled to -0.01 % a^{-1} (-0.49 to 0.48) with I^2 = 0%, the western Himalaya to -0.30, the central Himalaya to -0.28 and the eastern Himalaya to -0.68 % a^{-1}. The Karakoram indicator, +0.35 % a^{-1}, was not significant (p = 0.27) because the sub-regional pooled values have wide intervals, and there was no significant relation with period midpoint. Egger's test was strongly significant ($p < 0.001$), driven by the three decadal values of Bajracharya et al. (2014) for Bhutan, whose stated uncertainties of ±0.1% per decade are an order of magnitude smaller than those of any other study and which consequently receive most of the weight in the eastern Himalaya. Dropping that source gave a pooled rate of -0.26 % a^{-1} (-0.41 to -0.11) and I^2 = 73%. The unweighted means of the 25 basin-scale rates compiled by Bolch et al. (2012) without uncertainties, −0.43 % a^{-1} in the western Himalaya (n = 12) and −0.48 % a^{-1} in the central Himalaya (n = 10), are more negative than the weighted values, which again reflects the influence of a few precise, long-period inventories. We regard the area-change synthesis as indicative only.

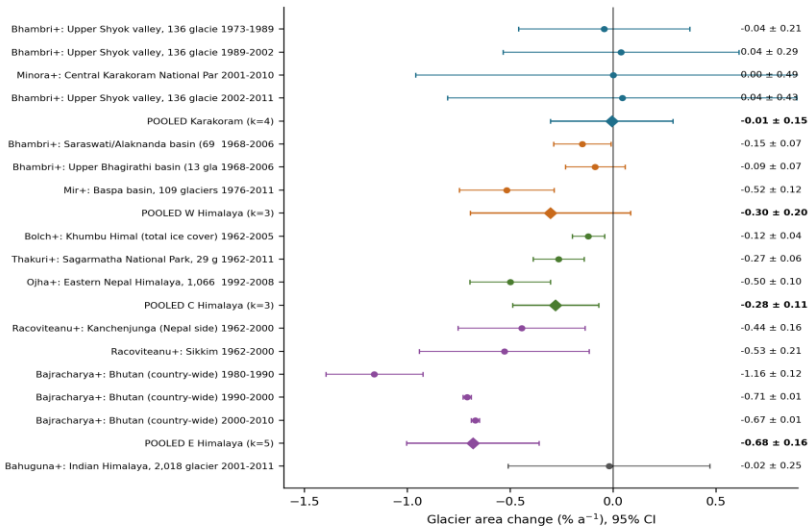

Figure 4. Forest plot of glacier area change rates with published uncertainty. Rates derived from a printed total change and period are marked in the coding sheet.

4. DISCUSSION

4.1 What the weighted record says

The published record, weighted by its own uncertainties, places Himalayan glaciers at about −0.4 m w.e. a^{-1} in the west and centre and between −0.2 and −0.4 m w.e. a^{-1} in the east, and the Karakoram at −0.06 m w.e. a^{-1}. These values are consistent with the direct regional syntheses of Brun et al. (2017), who found −0.37 for Spiti-Lahaul, −0.34 and −0.33 for west and east Nepal, −0.42 for Bhutan and −0.03 for the Karakoram over 2000 to 2016, and with the Himalaya-wide 2000 to 2016 value of −0.43 of Maurer et al. (2019). That the pooled values sit so close to the best single estimates is itself a result: it shows that the older, smaller and noisier studies do not, once weighted, pull the record away from the modern geodetic picture. It also shows where they add information. The pre-2000 record consists largely of these older studies, and it is the weighted pooling of them that gives the pre-2000 Himalayan value of -0.32 m w.e. a^{-1} used in the H1 comparison.

Heterogeneity is the other main finding. Roughly three quarters of the between-estimate variance is explained by sub-region and scale, and the residual I^2 of about 51% is what remains after those are accounted for. The Karakoram is remarkable in this respect: thirteen estimates from seven groups, three sensor types and periods from 1973 to 2016 are homogeneous. The central Himalaya is the opposite, with I^2 above 70% even after clustering by source, and the within-region spread is dominated by single-glacier estimates from the Everest region that range from −0.03 (Mera) to −1.24 m w.e. a^{-1} (West Changri Nup) over the same years (Sherpa et al., 2017). This is real variability, not noise, and it is the reason a regional mean from a handful of monitored glaciers cannot be extrapolated.

4.2 The acceleration question

The failure of the between-study test for H1 alongside the success of the within-study test deserves comment because it bears on how the literature is read. Papers that difference DEMs across two epochs for the same glaciers consistently report acceleration (Maurer et al., 2019; King et al., 2019; Bhattacharya et al., 2021), and our pooled within-study change of about −0.14 m w.e. a^{-1} is in line with the doubling from −0.22 to −0.43 m w.e. a^{-1} reported by Maurer et al. (2019). But the pre-2000 and post-2000 populations of independent estimates overlap so heavily, because different studies sample different glaciers, sub-regions and sensor combinations, that the same shift is not detectable between studies. Two consequences follow. First, statements that Himalayan mass loss has accelerated should rest on within-study comparisons, which are the appropriate design, and not on the contrast between older and newer literature. Second, the change is modest relative to the regional differences: the post-2000 shift is less than half the Karakoram-Himalaya difference and less than the spread among neighbouring glaciers in the Everest region.

4.3 The method effect is a selection effect

The result for H3 clarifies a point that has been made qualitatively several times (Cogley, 2011; Bolch et al., 2012; Azam et al., 2018). In situ series are more negative than the regional record, but geodetic estimates for the same glaciers are just as negative, and where both methods have been applied to the same glacier over the same years they agree within their uncertainties. The bias in the in situ record is therefore a sampling bias. Monitored glaciers are small, mostly debris-free, accessible and located in the accumulation-poor lower part of the elevation range, and small glaciers with low median elevations lose mass fastest (Brun et al., 2017; King et al., 2019). This has a practical implication for regional syntheses that combine in situ and geodetic data, such as the global assessments of Zemp et al. (2019) and Hugonnet et al. (2021): the in situ series should be treated as glacier-specific observations, useful for calibration and for seasonal and interannual variability, and not as regional samples. It also means that the screening of flawed series proposed by Azam et al. (2018), while valuable, will not on its own bring the in situ mean into agreement with the regional geodetic mean, because the remaining difference is geographic.

4.4 Comparison with previous syntheses

Previous reviews reached similar qualitative conclusions, and the value of the present analysis lies in what it adds. Bolch et al. (2012) inferred a Karakoram anomaly and a roughly −0.3 m w.e. a^{-1} Himalayan balance from inspection of their tables; we confirm both and attach intervals and a test. Azam et al. (2018) reported that in situ and remotely sensed balances agree better after screening; we show that the residual disagreement is explained by scale. Bolch et al. (2019) tabulated regional averages across all study types; our weighted values agree with theirs for the Karakoram and central Himalaya, are less negative for the western and eastern Himalaya, and carry uncertainties and heterogeneity statistics that the averages lack. Kääb et al. (2015)

discussed contending regional estimates for 2003 to 2008 without pooling them; the meta-regression shows that once sub-region is controlled the altimetry estimates are not distinguishable from the DEM-differencing estimates.

4.5 Limitations

Several limitations should be stated plainly. The estimates are not independent in the way meta-analysis assumes. Different studies difference the same DEMs (SRTM in particular) over overlapping glacier samples, and the three-level model accounts for clustering within sources but not for shared data across sources; the true precision of the pooled values is therefore somewhat lower than the intervals suggest. The uncertainties were taken as published and as one standard error, and the sources are not uniform in how they were derived; the halving sensitivity analysis bounds the consequence for the pooled values but not for the heterogeneity statistics. The literature harvest was seeded from compilation tables and citation tracking of the major syntheses rather than from a documented database search, and a full search with an explicit string and PRISMA flow (Page et al., 2021) should be completed before the estimate set is regarded as exhaustive; we expect it to add glacier- and basin-scale estimates rather than to change the regional values, because the regional syntheses are few and were all included. Ten values were read from compilation tables rather than the primary paper, and although the sensitivity analysis shows they do not affect the results, primary verification of the five that carry the most weight (the Fujita and Nuimura, 2011 and Ma et al., 2010 geodetic values and the Kääb et al., 2012 sub-regional values) is desirable. Estimates without printed uncertainties, which include almost all glaciological series before 2000 and most basin-scale area changes, could not be weighted; this is a limitation of the literature rather than of the method, and it argues for the routine reporting of uncertainties. The eastern Himalaya is represented by only four mass-balance estimates, and the pre-2000 Karakoram by two. Finally, the area-change synthesis is limited by the small number of studies with uncertainties and by the dominance of one source, and should be repeated when more inventories with error estimates are available.

5. CONCLUSIONS

A formal weighted synthesis of published estimates gives a Himalaya-Karakoram mass balance of -0.28 m w.e. a^{-1} (95% CI -0.37 to -0.19) with high heterogeneity, three quarters of which is explained by sub-region and spatial scale. The Karakoram anomaly is confirmed as a difference of about +0.34 m w.e. a^{-1} relative to the Himalaya over matched periods, precise, homogeneous and robust to every sensitivity test. Acceleration of Himalayan mass loss after 2000 is present in within-study comparisons at about −0.14 m w.e. a^{-1} but is not detectable between studies, indicating that it is small relative to the spread of the published record. The negative offset of glaciological series relative to geodetic estimates is explained entirely by the scale and selection of the monitored glaciers and is not a method artefact. Area change pools to about −0.3 % a^{-1} but the weighted synthesis is not yet robust. The main obstacle to synthesis is no longer the number of studies but the absence of reported uncertainties in a large part of the record; we recommend that future glacier-change studies report an uncertainty for every headline value, state its confidence level, and give sub-period estimates that partition the full period, so that the record can be pooled rather than merely listed.

Data availability

The coding sheet with every extracted value, its source DOI, extraction note and inclusion status, and the analysis scripts that reproduce all tables and figures, are provided as supplementary material.

Tables

Table 1. Pooled specific mass balance by sub-region and era (three-level REML). CI, confidence interval with Knapp-Hartung adjustment; PI, 95% prediction interval.

Set	k	Pooled (m w.e. a−1)	95% CI	τ^2 total	I^2 (%)	Q (df), p	95% PI
All estimates (three-level)	56	-0.28	-0.37 to -0.19	0.0414	83	257.4 (55), <0.001	-0.70 to 0.14

All estimates (two-level)	56	-0.28	-0.34 to -0.21	0.0352	81	257.4 (55), <0.001	-0.66 to 0.10
Sub-regional estimates only	51	-0.28	-0.38 to -0.18	0.0461	84	252.5 (50), <0.001	-0.72 to 0.16
Karakoram	13	-0.06	-0.10 to -0.02	0.0000	0	9.5 (12), 0.659	-0.10 to -0.02
Karakoram, midpoint pre-2000	2	-0.08	-0.44 to 0.28	0.0000	0	0.7 (1), 0.399	n/a
Karakoram, midpoint post-2000	11	-0.05	-0.10 to 0.00	0.0000	0	8.1 (10), 0.616	-0.11 to 0.00
W Himalaya	6	-0.38	-0.49 to -0.26	0.0000	0	4.3 (5), 0.506	-0.50 to -0.25
W Himalaya, midpoint post-2000	5	-0.39	-0.51 to -0.27	0.0000	0	0.4 (4), 0.981	-0.53 to -0.25
C Himalaya	28	-0.40	-0.53 to -0.28	0.0360	73	100.8 (27), <0.001	-0.81 to 0.00
C Himalaya, midpoint pre-2000	10	-0.37	-0.54 to -0.20	0.0323	79	44.4 (9), <0.001	-0.82 to 0.08
C Himalaya, midpoint post-2000	18	-0.40	-0.59 to -0.20	0.0486	71	50.8 (17), <0.001	-0.90 to 0.10
E Himalaya	4	-0.28	-0.54 to -0.02	0.0124	48	5.5 (3), 0.139	-0.87 to 0.32
E Himalaya, midpoint post-2000	3	-0.36	-0.81 to 0.09	0.0089	27	2.4 (2), 0.298	-2.14 to 1.43
Himalaya-wide	5	-0.25	-0.36 to -0.15	0.0002	2	3.7 (4), 0.447	-0.39 to -0.12
Himalaya-wide, midpoint pre-2000	2	-0.24	-1.18 to 0.70	0.0000	0	0.0 (1), 0.850	n/a
Himalaya-wide, midpoint post-2000	3	-0.30	-0.64 to 0.03	0.0089	47	3.6 (2), 0.162	-1.85 to 1.25
Method: geodetic	43	-0.25	-0.34 to -0.15	0.0336	80	181.0 (42), <0.001	-0.63 to 0.13
Method: altimetry	6	-0.28	-2.86 to 2.29	1.0207	100	33.0 (5), <0.001	-4.23 to 3.67

Method: glaciological	7	-0.62	-0.95 to -0.29	0.0557	50	10.9 (6), 0.092	-1.31 to 0.08
Scale: glacier	15	-0.54	-0.74 to -0.34	0.0702	80	52.1 (14), <0.001	-1.15 to 0.06
Scale: basin	11	-0.19	-0.29 to -0.09	0.0094	50	18.4 (10), 0.049	-0.43 to 0.05
Scale: subregion	25	-0.20	-0.27 to -0.12	0.0171	72	78.9 (24), <0.001	-0.48 to 0.08
Scale: region	5	-0.25	-0.36 to -0.15	0.0002	2	3.7 (4), 0.447	-0.39 to -0.12

Table 2. Tests of H1 and H2. Coefficients in m w.e. a−1 with Knapp-Hartung standard errors and p-values.

Model	k	Contrast	Estimate	SE	95% CI	p
H1 Himalaya: post-2000 indicator	43	post-2000 vs pre	-0.07	0.07	-0.20 to 0.06	0.306
H1 Himalaya: period midpoint	43	per decade	-0.04	0.03	-0.10 to 0.03	0.255
H1 Himalaya: adjusted for method and scale	43	post-2000 vs pre	-0.09	0.06	-0.21 to 0.04	0.170
H1 Himalaya: geodetic only	31	post-2000 vs pre	-0.08	0.07	-0.21 to 0.05	0.234
H1 Himalaya: compilation values dropped	34	post-2000 vs pre	-0.11	0.07	-0.24 to 0.03	0.138
H1 Karakoram: post-2000 indicator	13	post-2000 vs pre	+0.03	0.04	-0.04 to 0.10	0.431
H1 within-study differences (Himalaya)	5	post minus pre	-0.14	0.08	-0.29 to 0.01	0.059 (KH 0.133)
H1 within post-2000 estimates: midpoint trend	26	per decade	-0.10	0.17	-0.44 to 0.24	0.555
H2 all sub-regional, adjusted for midpoint	51	Karakoram vs Himalaya	+0.34	0.05	0.23 to 0.44	<0.001
H2 post-2000 estimates	37	Karakoram vs Himalaya	+0.34	0.05	0.24 to 0.45	<0.001
H2 periods within 1999-2016	32	Karakoram vs Himalaya	+0.34	0.05	0.25 to 0.43	<0.001
H2 post-2000, adjusted for method and scale	37	Karakoram vs Himalaya	+0.26	0.05	0.16 to 0.35	<0.001
H2 pre-2000 estimates	14	Karakoram vs Himalaya	+0.27	0.15	-0.02 to 0.56	0.097

H2 post-2000, flagged value dropped	36	Karakoram vs Himalaya	+0.34	0.05	0.23 to 0.44	<0.001
H2 post-2000, compilation values dropped	32	Karakoram vs Himalaya	+0.35	0.08	0.20 to 0.50	<0.001
H2 post-2000, two-level model	37	Karakoram vs Himalaya	+0.31	0.06	0.19 to 0.42	<0.001

Table 3. Full meta-regression model of record for sub-regional estimates (k = 51). Reference category: Karakoram, geodetic, sub-region scale, midpoint 2000.

Term	Estimate (m w.e. a−1)	SE (KH)	p
Intercept (Karakoram, geodetic, sub-regional, midpoint 2000)	+0.00	0.11	0.977
W Himalaya	-0.27	0.08	0.003
C Himalaya	-0.26	0.06	<0.001
E Himalaya	-0.24	0.09	0.014
Period midpoint (per decade)	-0.04	0.06	0.473
Glaciological	-0.12	0.13	0.353
Altimetry	-0.07	0.11	0.519
Glacier scale	-0.20	0.09	0.023
Period length (per decade)	-0.02	0.05	0.734
Residual τ^2 (total); I^2	0.0115	51%	
Variance explained vs. intercept-only model	75%		

Table 4. Tests of H3 and sensitivity analyses.

Analysis	k	Estimate (m w.e. a−1)	95% CI	p / I^2
H3 crude: glaciological vs geodetic	50	-0.31	-0.57 to -0.05	p = 0.026
H3 adjusted for sub-region and midpoint	50	-0.21	-0.45 to 0.02	p = 0.081
H3 glacier-scale estimates only	15	+0.04	-0.38 to 0.45	p = 0.871
H3 post-2000, adjusted for scale	34	+0.10	-0.32 to 0.52	p = 0.635
H3 matched pairs (glaciological minus geodetic)	4	+0.08	-0.14 to 0.30	I^2 = 0%
Overall, flagged value dropped	55	-0.28	-0.37 to -0.19	I^2 = 83%
Overall, compilation values dropped	46	-0.24	-0.33 to -0.15	I^2 = 75%
Overall, uncertainties halved (2σ)	56	-0.30	-0.40 to -0.20	I^2 = 97%
Overall, inverse-variance fixed effect	56	-0.21	-0.24 to -0.19	
Overall, unweighted mean	56	-0.31	SE 0.04	

Leave-one-source-out range	56	-0.29 to -0.25		
Egger regression, all estimates	56	intercept -0.077	SE 0.047	p = 0.108
Egger regression, geodetic only	43	intercept -0.084	SE 0.059	p = 0.158

Table 5. Pooled glacier area change (% a−1), three-level REML.

Set	k	Pooled (% a−1)	95% CI	I^2 (%)
All estimates (three-level)	16	-0.32	-0.52 to -0.13	98
All estimates (two-level)	16	-0.37	-0.56 to -0.19	99
Karakoram	4	-0.01	-0.49 to 0.48	0
W Himalaya	3	-0.30	-1.16 to 0.55	91
C Himalaya	3	-0.28	-0.75 to 0.19	88
E Himalaya	5	-0.68	-1.14 to -0.22	99
All estimates, Bajracharya et al. (2014) dropped	13	-0.26	-0.41 to -0.11	73
Karakoram vs Himalaya (adjusted for midpoint)	15	+0.35	-0.25 to 0.95	p = 0.273
Period midpoint, Himalaya (per decade)	11	+0.13	-0.02 to 0.28	p = 0.127
Egger regression	16	intercept -0.708	SE 0.036	p = <0.001

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