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Brief Communication: Contending estimates of early 21st century glacier mass balance over the Pamir-Karakoram-Himalaya

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Abstract

We present glacier thickness changes over the entire Pamir-Karakoram-Himalaya arc based on ICESat satellite altimetry data for 2003–2008. The strongest thinning ($< -1\,\mathrm{m\,yr^{-1}}$) is observed for the East Nyainqêntanglha Shan. Conversely, glaciers of the West Kunlun Shan are slightly gaining volume, and Pamir and Karakoram seem to be on the western edge of an anomaly rather than its centre. For the Ganges, Indus and Brahmaputra basins, the glacier mass change reaches $-22 \pm 3\,\mathrm{Gt\,yr^{-1}}$, about 10 % of the current glacier contribution to sea-level rise. For selected catchments over the study area we estimate glacier imbalance contributions to river runoff from a few percent to far over 10 %. We highlight the importance of C-band penetration for studies based on the SRTM elevation model. To the very east and west of our study area, this penetration seems to be of larger magnitude and variability than previously assumed.

1 Introduction

Region-wide measurements of glacier volume or mass change are limited for the Pamir-Karakoram-Himalaya region, leaving room for large speculations about the glacier response to climate change and its hydrological significance. Between a handful of studies that narrow down the range of uncertainties for core parts of this remote mountain region, significant inconsistencies exist. The aims of this study are to provide (i) a new consistent regional-scale data set from the ICESat campaign (2003–2008) by extending Kääb et al. (2012) to completely cover the study region by Gardelle et al. (2013) and several major river basins, and (ii) to compare the results to other previous estimates of the Pamir-Karakoram-Himalaya glacier volume change.

Glacier mass change in high mountain Asia (or some part of it) have been obtained (i) by extrapolating the few existing in-situ mass balance series (Cogley, 2011; Bolch et al., 2012; Yao et al., 2012), (ii) using space gravimetry (Jacob et al., 2012; Gardner et al., 2013), (iii) laser altimetry (Kääb et al., 2012; Gardner et al., 2013; Neckel et al., 2014), and (iv) the differencing of digital elevation models (Gardelle et al., 2013).

Here, we derive a consistent 2003–2008 ICESat-based estimate of mass change for the entire pan-Himalayan region following methods explained in Kääb et al. (2012) with a considerable extension of the latter study towards the East Nyainqêntanglha Shan, the Pamir and part of the Tibetan Plateau. In short, ICESat footprints are intersected with the SRTM DEM and the most snow-free multispectral Landsat images over ~ 2000–2013 to manually classify footprints into three classes; glaciers, non-glaciers and water. Glacier elevation difference trends are then estimated regionally and at a $1^\circ \times 1^\circ$ geographic grid by fitting a robust linear temporal trend to the time series of elevation differences between the SRTM DEM and individual ICESat footprint elevations. Trends are derived from autumn ICESat campaigns only, because combined autumn and winter trends are sensitive to temporal variations in accumulation amount and timing, potentially introducing bias (see Supplement of Kääb et al., 2012). We ensure that our trends are not due to sampling bias of ICESat elevations by comparing ICESat elevation histograms with glacier hypsometry. The resulting elevation difference trends for all our zones are given in Table 1.

2 Glacier thickness changes

2.1 Thickening in the Karakoram and West Kunlun Shan

A first striking feature in the regional map of elevation difference trends (Fig. 1) is glacier thickness gain in the West Kunlun Shan ($\sim +0.1\,\mathrm{m\,yr^{-1}}$), agreeing with in-situ mass balance and length change measurements (Yao et al., 2012). There is a southwest to northeast gradient from considerably negative glacier mass balances in Hindu Kush and Spiti Lahaul to positive values in the Pamir-Karakoram-West Kunlun Shan region (Fig. 1). This suggests the so-called Karakoram glacier mass-balance anomaly (Hewitt, 2011; Gardelle et al., 2012a), or Pamir-Karakoram anomaly (Gardelle et al., 2013), is rather the edge or southwest limit of an anomaly centred more to the north-east over the West Kunlun Shan, or Tarim basin. The anomaly is thus not necessarily due to peculiarities of the Karakoram topography or glaciers (e.g. surge type, hypsometry, avalanche contribution; Hewitt, 2011), but a result of a larger-scale meteorological or climatic feature. Using results from Gardner et al. (2013) and Neckel et al. (2014) combined with the glacier elevation change pattern of Fig. 1 suggest the centre of the anomaly could be located over the Tibetan Plateau. Direct precipitation measurements in this region are scarce thus trends uncertain. Satellite-retrieved precipitation and gauge data (Global Precipitation Climatology Project) suggests an increase of precipitation over the study region north of Karakoram and east of Pamir (Yao et al., 2012). Chinese measurements show increased precipitation over the Tibetan Plateau (X. Chong-Yu, personal communication, 2014), and Tao et al. (2014) suggest wetter conditions over the Tarim basin since the mid 1980s. A number of abnormally wet years occurred during the early 21st century over the Tarim basin and the Tibetan Plateau (Becker et al., 2013), in particular for the hydrological years 2003/2004 and 2005/2006. A recent climate modelling study (Kapnick et al., 2014) proposes that stable or increasing snowfalls characterise the Karakoram anomaly on a background of increasing air temperatures. Despite the available studies and data, further research seems necessary to consolidate the precipitation and temperature trends and the reason behind the slight glacier volume gains.

2.2 Massive thinning in East Nyainqêntanglha Shan and Jammu-Kashmir

The other striking feature in Fig. 1 is the massive glacier thickness loss in the East Nyainqêntanglha Shan to the very east (between -1 and $-1.7\,\mathrm{m\,yr^{-1}}$), also consistent with the large negative in-situ mass balances and frontal retreats in this zone (Yao et al., 2012). The glaciers of East Nyainqêntanglha Shan have the smallest total elevational range in our study region, indicating a large sensitivity to fluctuations in the equilibrium line altitude (Pelto, 2010; Loibl et al., 2014). The few available in-situ mass balance measurements in the area suggest that the equilibrium line was over the vertical limits of the monitored glaciers in the late 2000s, and precipitation in this zone shows the strongest long-term decrease over the entire Pamir-Karakoram-Himalaya region (Yao et al., 2012; Becker et al., 2013). A similar pattern of glacier shrinkage, though less distinct, is found in Jammu Kashmir within our Spiti Lahaul zone and forms the cluster of second-largest thickness loss rates in this study (-0.5 to $-0.7\,\mathrm{m\,yr^{-1}}$). Also here, Landsat data indicate widespread loss of large parts of accumulation areas.

2.3 Comparison to previous thickness change studies

The following comparison to other studies uses average glacier thickness changes rather than mass changes in order to minimize effects from different delineations of study zones, glacier cover areas, and density assumptions. From Hindu Kush and Karakoram in the west to Nepal in the east, results of all studies agree within their errors (Table 1). Results are most sensitive to zone delineation in the Hindu Kush, reflecting the strong spatial variability of glacier thickness change rates in this area (Fig. 1) and presumably also locally heterogeneous glacier behaviour (Sarikaya et al., 2012; see also below for Pamir).

Significant differences between the results of all studies are found over East Nyainqêntanglha Shan. Our results and those from Neckel et al. (2014) agree within the errors, but not with Gardner et al. (2013) although all three studies are based on ICESat. While this study and Neckel et al. use ICESat footprint classifications from contemporary satellite images, Gardner et al. use Randolph Glacier Inventory outlines (RGI version 2.), which contain considerable errors in this zone (see Table 1 in Gardelle et al., 2013). Repeating our analysis with footprint classifications based on the Randolph Glacier Inventory results in roughly 20 % less negative glacier elevation difference trends from inclusion of non-glacier footprints and in negative land trends from inclusion of glacier footprints. The remaining discrepancy is presumably due to the fact that the ICESat-based results of Gardner et al. are averaged from three different methods. Their results based on autumn footprints only (method B, Gardner et al., 2013) suggest a thickness change rate of $-0.86\,\mathrm{m\,yr^{-1}}$, which is in closer agreement with our results.

At a first glance, East Nyainqêntanglha Shan results from Gardelle et al. (2013; zone called there Hengduan Shan) and Gardner et al. (2013) seem to agree, but we believe this might be a coincidence. First, above we argue why the Gardner et al. results might be too negative. Second, the results in Gardelle et al. (2013) rely crucially on an estimate of SRTM C-band penetration. Over any glacier globally, the SRTM radar waves will typically have penetrated into the snow and ice, with potential largest penetration depths through snow and firn, and smallest through ice (Kääb et al., 2012; Dall et al., 2001; Rignot et al., 2001). As a consequence, SRTM glacier elevations do in general not reflect real mid-February 2000 glacier surface elevations but some lower horizon, the elevation of which depends among others on the dielectric properties and structure of the penetrated glacier volume during the SRTM campaign. For elevation difference studies where one of the elevation data sets is the SRTM, its penetration depth needs to be estimated for correction, and biases in this estimate translate directly into offsets in thickness change. While Gardelle et al. (2013) used an average C-band penetration of 1.7 m for East Nyainqêntanglha Shan (estimated from the difference of SRTM C-band and X-band DEMs, Gardelle et al., 2012b), extrapolation of our ICESat trends to February 2000 (for method and discussion see Kääb et al., 2012) indicates a much higher average penetration of 8–10 m (7–9 m if based on the winter trends that might alternatively be assumed to reflect February conditions), while the corresponding off-glacier penetration is not discernible from zero. Clearly, our penetration depth lies at the high end, but remains within the range of possible C-band phase-centre penetrations (Kääb et al., 2012; Dall et al., 2001; Rignot et al., 2001). Sakai et al. (2014) suggest the highest accumulation rates of the entire study region occur in East Nyainqêntanglha Shan, together with Hindu Kush. Correction of the Gardelle et al. (2013) results by our present C-band penetration estimate completely reconciles their results with ours. Note, however, that extrapolation of our 2003–2008 elevation difference trend back to 2000 is based on the strong assumption that the 2000–2003 trend equals the 2003–2008 trend.

For the Bhutan zone, Gardelle et al. (2013) estimated a C-band penetration for February 2000 of 2.4 m whereas our extrapolation of ICESat trends suggests around 6 m, which again is able to reconcile the results of both studies for this zone.

In the Pamir, our results are more negative than Gardner et al. (2013) and in particular Gardelle et al. (2013). As above, we suggest that our manual classification of ICESat footprints vs. the Randolph Glacier Inventory contributed to the difference with Gardner et al. (2013) (Gardelle et al., 2013 used their own inventory). Also, the difference between our study and Gardner et al. (2013) is reduced if only the results from their Method B (similar to ours) is considered. Gardelle et al. (2013) find glacier thickness changes of $+0.16 \pm 0.15\,\mathrm{m\,yr^{-1}}$ over the Pamir whereas the present study suggests $-0.48 \pm 0.08\,\mathrm{m\,yr^{-1}}$. Again, we find larger SRTM C-band penetration of 5–6 m compared to 1.8 m (Gardelle et al., 2013). Applying the average C-band penetration from the present study is again able to completely reconcile the results of both studies. However, comparison of both studies over the Pamir is complicated by a number of glacier surges (Gardelle et al., 2013) in connection with particularly sparse ICESat glacier coverage. Visual inspection shows some ICESat tracks crossing areas of strong positive or negative elevation changes from surge waves. The different observation periods for both studies (2000–2011 vs. 2003–2008) may also have considerable impact due to surge activities and climate inter-annual variability (Yi and Sun, 2014).

3 Glacier mass changes and water resources

We assumed an average density of $850\,\mathrm{kg\,m^{-3}}$ for all 2003–2008 volume changes (Huss, 2013; see Kääb et al., 2012 for different density scenarios) and used area estimates for the complete glacier cover based on scaling the density of ICESat footprints on glaciers with the areas and footprint densities of entire zones (Kääb et al., 2012), to convert the thickness changes to water equivalent quantities (Table 2). Our method to estimate the total glacier areas is certainly open to discussion, but we preferred the above procedure over using areas from the Randolph Glacier Inventory because of the large deviations to our estimates, mainly for East Nyainqêntanglha and Pamir, from the obviously outdated glacier outlines and voids in the Randolph inventory (cf. Nuimura et al., 2014). The uncertainty of water equivalent quantities is estimated as root sum square of the standard error of the elevation difference trend fit, the off-glacier trends, an error due to temporal offset of the ICESat autumn campaigns from maximum cumulative ablation conditions, an uncertainty of ±20 % for the glacier cover areas, and an uncertainty of ±60 $\mathrm{kg\,m^{-3}}$ for density (Kääb et al., 2012; Huss, 2013). Note that water equivalent results from this study are not identical to Kääb et al. (2012), even if elevation difference trends agree, due to the simplified density assumption and the different glacier area estimates used.

3.1 Comparison to gravimetric mass loss

For the Pamir, Kunlun Shan and Karakoram (zone 8b of Jacob et al., 2012; note that the Karakoram is part of their zone 8b, not 8c as suggested by their zone names) we estimate a glacier mass change of $-6\pm2\,\mathrm{Gt\,yr^{-1}}$ for 2003–2008 that agrees well within the error to Jacob et. al. results from satellite gravimetry of $-5\pm10\,\mathrm{Gt\,yr^{-1}}$ (January 2003–December 2007) and $-8\pm9\,\mathrm{Gt\,yr^{-1}}$ (January 2004–December 2008). For the Himalayas and East Nyainqêntanglha Shan (zone 8c of Jacob et al., 2012) we estimate a 2003–2008 glacier mass change of $-19\pm3\,\mathrm{Gt\,yr^{-1}}$ that compares to $-3\pm12\,\mathrm{Gt\,yr^{-1}}$ (January 2003–December 2007) and $-2\pm10\,\mathrm{Gt\,yr^{-1}}$ (January 2004–December 2008) from satellite gravimetry. Given their fundamentally different approaches, it is challenging to discuss potential sources of disagreement between the two studies in the Himalayas and East Nyainqêntanglha. Groundwater depletion (Rodell et al., 2009), glacier imbalance runoff into endorheic basins (Zhang et al., 2013), and errors and biases in the ICESat-derived trends as discussed above and in Kääb et al. (2012) are all likely explanations. Note, Gardner et al. (2013), offer a second, more negative gravimetric estimate for the entire combined High Mountain Asia that is, though, not spatially resolved enough to compare to our results. (The uncertainties of our results in this entire paragraph are given at 2σ confidence level to better agree with the uncertainty level in Jacob et al. (2012), whereas elsewhere in this contribution uncertainty is given at 1σ confidence level.)

3.2 River runoff

The glaciers of the Tarim basin (only 40 % of total glacier area is covered here, with notably Tien Shan missing) and the Amu Darya basin (all glacier areas covered) drain into endorheic basins and thus their mass changes do not contribute to sea-level (Table 2). The glacier mass changes in the Indus, Ganges and Brahmaputra basins contributed together $\sim 0.06 \pm 0.01\,\mathrm{mm\,yr^{-1}}$ to eustatic sea-level rise, that is $\sim 10\,\%$ of the current sea level contribution of $0.71 \pm 0.08\,\mathrm{mm\,yr^{-1}}$ (Gardner et al., 2013) from glaciers outside the ice sheets.

The discharge equivalent of these mass changes, that is the annual average glacier imbalance contribution to river runoff, is given in Table 2 for the major river basins covered. The Tarim basin glaciers stored water over 2003–2008. The glacier imbalance contribution to runoff is largest for Brahmaputra ($-400 \pm 60\,\mathrm{m^3\,s^{-1}}$ discharge equivalent, DE), followed by the Indus ($-220\,\mathrm{m^3\,s^{-1}}$ DE) and Ganges ($-130\,\mathrm{m^3\,s^{-1}}$ DE). The imbalance DEs calculated here relate to runoff at the glaciers. Comparison to measured river runoff is thus biased the further downstream the gauging stations are situated due to upstream losses. It is important to note that the available runoff data from literature and databases refer to various time periods, in parts considerably older than the ICESat period. Figure 2 illustrates thus only roughly the hydrological significance of the 2003–2008 glacier mass change in selected catchments.

The modelling results for “non-renewable glacier runoff” of Savoskul and Smakhtin (2013) agree well with ours for Amu Darya, less for Indus (they obtain $-0.55\,\mathrm{m\,w.e.\,yr^{-1}}$ specific mass loss rate over 2001–2010, we $-0.28\,\mathrm{m\,w.e.\,yr^{-1}}$) and Ganges (they obtain $-0.77\,\mathrm{m\,w.e.\,yr^{-1}}$, we $-0.37\,\mathrm{m\,w.e.\,yr^{-1}}$), and not very well for Brahmaputra (they obtain $-0.36\,\mathrm{m\,w.e.\,yr^{-1}}$, we $-0.90\,\mathrm{m\,w.e.\,yr^{-1}}$).

4 Conclusions

From 2003–2008 ICESat-derived elevation difference trends over Pamir-Karakoram-Himalaya and from comparison to geographically overlapping studies we draw the following conclusions:

- Glacier thickness loss over the study region is most pronounced for the East Nyainqêntanglha Shan, followed by Jammu-Kashmir. In these regions, the firn lines seem to have risen towards or above the maximum glacier elevations.
- Glaciers in and around the West Kunlun Shan are in balance or even gaining volume, and Pamir and Karakoram seem to be on the western limit of this anomaly rather than its centre. This suggests it is a meteorological or climatic anomaly (rise in precipitation) rather than caused directly by glaciological and topographic peculiarities in the Karakoram, even if these certainly influence the glaciological expression of the anomaly. But the cause and duration of this regional glacier anomaly is not fully understood yet.
- Volume change results are especially sensitive to spatial and temporal distribution of sampling in Pamir and, to a lesser extent Hindu Kush. The heterogeneous glacier behaviour in these two zones enhances uncertainty when extrapolating elevation difference trends from ICESat tracks, or areas covered by differential DEMs, to the entire zones.
- Extrapolation of ICESat trends to the SRTM acquisition date suggests a much larger magnitude and variability of SRTM C-band phase-centre penetration than previously assumed. Given the crucial importance of radar penetration for glacier thickness change studies based on radar DEMs, such as the SRTM or the upcoming TanDEM-X, we recommend to be critical against penetration assumptions used in previous studies and to investigate the issue more extensively and systematically (Langley et al., 2007; chapter 7 in Müller, 2011). The problem is

complicated by the fact that radar penetration has to be known specifically for certain dates back in the past. In fact, we are still puzzled about the seemingly large SRTM penetration we inferred in the East Nyainqêntanglha Shan (8–10 m) and Pamir (5–6 m).

- The glacier mass changes in the Tarim and Amu Darya basins of $+0.7 \pm 1.0\,\mathrm{Gt\,a^{-1}}$ and $-4.0 \pm 0.8\,\mathrm{Gt\,a^{-1}}$ do not contribute to sea level rise. The combined Ganges, Indus and Brahmaputra basin glacier mass change is $-23.7 \pm 2.1\,\mathrm{Gt\,yr^{-1}}$, almost 10 % of the glacier contribution to sea-level rise during 2003–2009.
- Neglecting water losses between the glaciers and gauging stations, the 2003–2008 glacier imbalances amount to ~ 6 % of the annual discharge of Amu Darya and Upper Indus where they leave the mountains. This is a considerable amount given the significance of the rivers for the Aral Sea (Amu Darya), and massive irrigation schemes and household use in these dry climate regions. Maximum glacier imbalance contributions to annual average river runoff are up to ~ 17 % as found for the Shyok (Indus) and ~ 10 % for Vaksh (Amu Darya), minimum contributions are only ~ 1–3 % for the monsoon-type catchments in Nepal.
- Our results on glacier mass loss agree with those from satellite gravimetry (Jacob et al., 2012) over Pamir, West Kunlun Shan and Karakoram, but significantly diverge over the Himalaya and East Nyainqêntanglha Shan.

It is important to note that our results only cover 5 years, 2003–2008, and it remains open to what extent those years are representative for longer periods, such as the 10 years covered by Gardelle et al. (2013). For short mass balance series, single anomalous years may have large impacts on trends. Our water equivalent results are also sensitive to density and glacier area assumptions. We find that glacier outlines and areas in the study region are still quite uncertain and invite the reader to use improved glacier area estimates for upscaling our results, and their own assumptions for the conversion of volume changes to mass changes.

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Table 1. Glacier elevation difference trends over the Pamir-Karakoram-Himalaya from this and other studies. Note that Gardelle et al. (2013) cover the period 2000 to ∼ 2010, while the other studies 2003 to 2008/2009. Note also that the zones of this study and Gardelle et al. coincide, whereas the zones of the others do so only roughly, which can potentially explain parts of the disagreements. See text in Sects. 3 and 4 for an explanation of how the glacier areas were estimated.

Zone	Glacier area (km^2)	This study (m yr^{-1}, ± at 1σ-level)	Gardner et al. (2013) (m yr^{-1}, ± at 2σ-level)	Neckel et al. (2014) (m yr^{-1}, ± at 1σ-level)	Gardelle et al. (2013) (m yr^{-1}, ± at 1σ-level)
East	6000	−1.34 ± 0.29	−0.30 ± 0.13	−0.81 ± 0.32	−0.39 ± 0.16
Nyainqêntanglha[1]			−0.40 ± 0.41[2]		
Bhutan	3500	−0.89 ± 0.16	−0.89 ± 0.18	−0.78 ± 0.27	−0.26 ± 0.15
Everest	8500	−0.37 ± 0.10	−0.44 ± 0.20		−0.30 ± 0.16
West Nepal	7500	−0.43 ± 0.09		−0.44 ± 0.26	−0.38 ± 0.16
Spiti Lahaul	9500	−0.49 ± 0.12	−0.53 ± 0.13		−0.53 ± 0.16
Karakoram	21 000	−0.10 ± 0.06	−0.12 ± 0.15		+0.12 ± 0.19
Hindu Kush	5500	−0.49 ± 0.10			−0.14 ± 0.19
Pamir	6500	−0.48 ± 0.14	−0.13 ± 0.22		+0.16 ± 0.15
West Kunlun Shan – Tarim	12 500	+0.05 ± 0.7	+0.17 ± 0.15	+0.03 ± 0.25	

[1] named Hengduan Shan in Gardelle et al. (2013);

[2] two zones of Gardner et al. (2013) overlap with our zone and both their values are given.

Table 2. Glacier thickness and mass changes over the major river basins of the study area. The discharge equivalent is a unit conversion from mass change and neglects any losses such as by evaporation or to groundwater.

Major river basin	Glacier area (km^2)	Elevation difference trend (m yr^{-1})	Mass change (Gt yr^{-1})	Discharge equivalent DE (m^3 s^{-1})
Tarim[1]	15 000	+0.06 ± 0.08	+0.7 ± 1.0	+24 ± 33
Amu Darya[2]	11 000	−0.43 ± 0.08	−4.0 ± 0.8	−128 ± 25
Indus	25 000	−0.33 ± 0.04	−7.0 ± 0.8	−220 ± 26
Ganges	11 000	−0.44 ± 0.07	−4.1 ± 0.6	−130 ± 20
Brahmaputra	14 000	−1.06 ± 0.15	−12.6 ± 1.9	−400 ± 60

[1] Tarim is an endorheic basin. Only parts (~ 40 %) of the glacier area within the Tarim basin are covered in this study. [2] Endorheic basin.

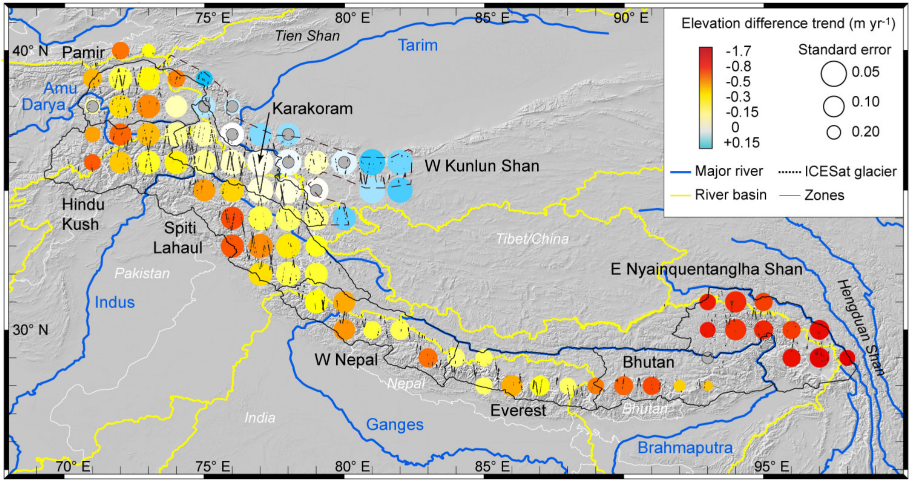

Figure 1. Study region and trends of elevation differences between ICESat and SRTM over 2003–2008. Data are shown on a 1° grid with overlapping rectangular geographic averaging cells of 2° × 2°. Trends are based on autumn ICESat acquisitions. Only ICESat footprints over glaciers are indicated. The zones indicated by black outlines are equivalent to the ones of Gardelle et al. (2013) with the W Kunlun Shan-Tarim zone (dashed outline) being the only additional one. Trends for all cells (coloured data circles) are statistically significant except for the cells that are marked with grey centres. The uncertainty of the temporal trends per cell is indicated through circle sizes indirectly proportional to the standard error of trends at 68 % level.

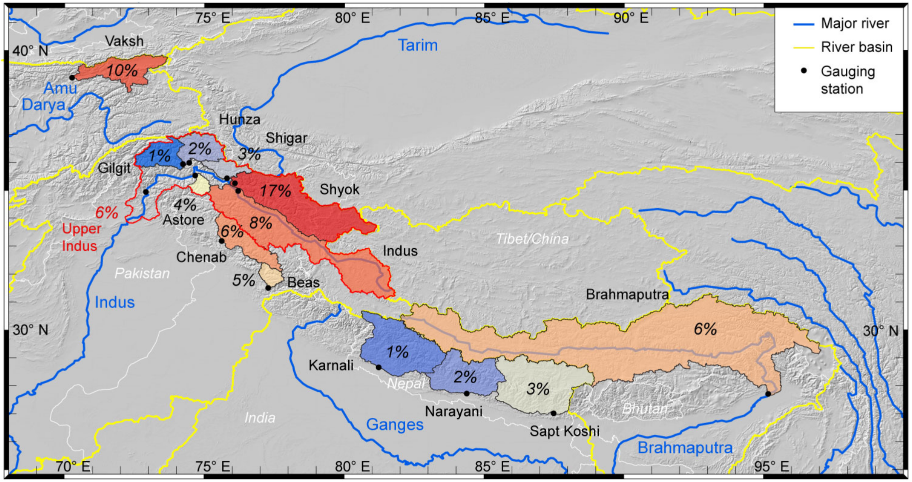

Figure 2. Percentage of discharge equivalent of annual glacier imbalance to measured average river runoff for selected catchments. Note that the actual numbers will be somewhat lower due to unaccounted water losses such as from evaporation or to groundwater. For details on the gauging stations used and the uncertainty of the contributions see Supplement.