Dear Etienne,

Thank you for your careful read. We have carefully revised the manuscript taking your comments into account and provide below a point to point reply. We used track changes so the all changes in the manuscript can be easily identified. We hope the manuscript can now be accepted.

With best regards,

Tobias Bolch on behalf of all authors

Reply to comments:
The comments are repeated in *italic*, our reply is given in **bold**.

Comments in the decision letter:
Supplement. Table S3. "Dates ASTER DTMs used" --> "Dates ASTER DTMs"
"(wighted mean" --> "(Weighted mean)
Corrected

P8, Fig. 3 "also show the total change from 1973-2009". If there is an added value to include the 1973-2009 elevation change you should add it. And I think there is definitively one. Indeed, this point makes me think that you need to clearly state earlier in the manuscript that the correction for penetration has been applied as a mean average (right? the mean value from Kaab et al. [2012]). If I understood correctly, you did not correct for variations of penetration as a function of altitude. Should be clearly stated. Then, this is a good reason to show the 1973-2009 dh value in Figure 3 because the values for subperiods including SRTM may be slightly biased because of higher penetration at high elevation than in the lower part.
Yes, we applied the penetration correction as a mean average and state this now in the revised text. We also added the profiles of the elevation changes for the entire period.

Annotated comments:
P1, comment 1: Replaced by something like "but only one mass budget analysis" to take into account the publication by Zhou et al.
We write now: "only very few", since there is also the data for Siachen Glaciers and maybe there is a (non-peer-reviewed) study, which we might have missed.

P1, comment 2: My advice would be to finish with an implication sentence rather than this technical point about the data used. To what extent your study will help other scientists
We present now the data used earlier in the abstract. There are several implications (such as for hydrological modelling, mass balance modelling understanding surge-type glacier) and we do not want to highlight a specific one.

P1, comment 3: I think Rankl et al. 2014 could be cited here also.
Reference cited as suggested.

P1, comment 4: Revised in view of the Zhou et al. JOG paper
We write now: „However, almost no mass budget analyses are available for Karakoram glaciers prior to the year 2000 are rare. While this paper was in open discussion,, Zhou et al. (2017) reported mass budgets −0.09 ± 0.03 m w.e. a-1 of for the period ~1970 to 2000. For Siachen Glacier in eastern Karakoram…

P1, comment 5: measurements, available since
We think that "measurements that are available since 1961" is more appropriate.

P2, comment 6: maybe add in the legend the source for the basin boundary, I do not think it was provided elsewhere.
The boundary was generated by ourselves by GIS analysis and crosschecked with a boundary for a study by Silvan Ragettli. We do not think it is really needed to add this information in the figure caption. However, we can write if you'd prefer.

P3, comment 1: always a space between number and unit
Space included between number and unit. We checked also the entire manuscript but did not find any other missing space.

P3, comment 2: what about the season of acquisition. Was it a selection criteria? If yes, as I suspect, then mention it.
Of course this was a selection criteria and thought it was clear from „minimum snow cover". However, we agree that this is not so obvious and include now "close to end of ablation season" as a selection criteria.

P3, comment 3: why difference? This is simply the mean of the dates of the two scenes right?
Yes, we use the mean of the time differences between the two acquisitions. Details are of the dates and the time difference are given in Table S3. We moved the sentence now to the section on the prostprocessing (see also your comment 2 on page 4.)

P3, comment 4: I suggest starting a new paragraph here
New paragraph started.

P4, comment 1: this statement is not clear to me. Is it the value of the horizontal shift that you found using NK2011 and that your applied?
Yes; we write now: "The final horizontal shift…"

P4, comment 2: not 100% clear to me. How the weight are applied. Do you consider each glacier separataly or work pixel by pixel?
We agree that the procedure was not 100% clearly described. We write now:
"To calculate surface elevation changes, we subtract each older DTM from more recent DTM, and mosaic the difference grids to facilitate processing. Where the ASTER DTMs from different time periods overlapped, we calculate a weighted mean elevation change based on the time of acquisition and glacier coverage (Figure S1, Table S3)."

P5, 5 comment 1: poor wording I think. Fourth author should check...
We improved the wording and write now: „The standard deviation of the non-glacierized terrain can serve as a first estimate of the uncertainty and is…"

P5, comment 2: move Delta_H to subscript
Corrected.

P6, comment: If you look carefully at their map you will discover many artefacts in their accumulation areas... coregistration was not perfect in this study. I do not want you to elaborate on this in the paper (not his scope) but just that you are aware of this
Thank you for the information.

P6, comment 2: other could argue that DLR deliver freely some TDX DEMs. Not really relevant, at least at this location in the paper
We removed "freely available".

P7, comment 1: little has been done to incorporate in the text the results for the 1974-2009 time period, although it was a strong comment of all reviewers. Maybe a few words are needed. Suggest a slight mass loss rather than balanced budget no?
We agree and address now more specific the entire study period. We also agree that results hint to on average to slight mass loss although the results are insignificant. We changes the statements accordingly and also adjusted the title to:
"Nearly balanced glaciers in the Hunza catchment (Karakoram) since the 1970s"

P8, comment 1: to be updated including Zhou et al. JOG
Updated accordingly.

P9, comment 1: Maurer
Corrected.

P9, comment 2: for the whole basin? For what period? 1973-2000?
Yes, for the whole basin and the period 1973 – 2009. This information is now included.

P10, comment 1: for what period?
A different penetration correction would affect both periods. We hence write now "±".

P10: comment 2: add "together with Zhou et al. (2017)" or something similar
P10: comment 3: The 1973-2009 mass balance suggests a slight mass loss...
We usually do not include references in the conclusion. We rewrote the conclusions and focus now more on our study region and the investigation on surge-type glaciers.

Brief Communication: ~~Glaciers~~Nearly balanced glaciers in the Hunza Catchment (Karakoram) ~~are in balance~~ since the 1970s

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Abstract. Previous geodetic estimates of mass changes in the Karakoram revealed balanced budgets or a possible slight mass gain since the year ~2000. Indications for longer-term stability exist but ~~no~~only very few mass budget analyses are available before 2000. Here, we show based on 1973 Hexagon KH9, ~2009 ASTER, and the SRTM DTM that glaciers in the Hunza River basin (Central Karakoram) were on average in balance or showed slight insignificant mass loss within the period ~1973 – 2009. Heterogeneous behaviour and frequent surge activities were also characteristic for the period before 2000. Surge-type and non-surge-type glaciers showed on average no significantly different mass change values. However, some individual glacier mass change rates differed significantly for the periods before and after ~2000. ~~These analyses are based on low cost stereo Hexagon KH9 images from the 1970s, freely available and automatically generated digital terrain models (DTMs) from ~2009 ASTER data, and the SRTM DTM.~~

1 Introduction

Glacier melt water is of high importance for the run-off of the Indus River (Immerzeel et al., 2010) but the exact glacier share is not known. This is partly due to the lack of knowledge about precipitation, snow cover, and snow water equivalent, but also about glacier mass balance, their characteristics and their responses to climate change. Karakoram glaciers, which occupy a large portion of the glacierized area of the Indus basin, have recently shown unusual behaviour: on average no significant area changes but frequent advances and surge activities have been observed during the last decades (Bhambri et al., 2013; Bolch et al., 2012; ~~Hewitt, 2011;~~ Copland et al., ~~2011~~2011; Hewitt, 2011; Rankl et al. 2014). Geodetic mass estimates revealed balanced glacier mass budgets or even slight mass gain since ~2000 (~~Rankl and Braun, 2016;~~ Gardelle et al., 2013; Kääb et al., 2015~~).~~; Rankl and Braun, 2016). However, ~~almost no~~ mass budget analyses ~~are available~~ for Karakoram glaciers prior to the year 2000~~. The only exception is~~ are rare. While this paper was in open discussion, Zhou et al. (2017) reported a Karakoram-wide mass budget of −0.09 ± 0.03 m w.e. a^{-1} for the period ~1970 to 2000. For Siachen Glacier in eastern Karakoram,~~ for which~~ Zaman and Liu (2015) corrected the erroneous value of -0.51 m w.e. a^{-1} given by

Bhutiyani (1999), and estimated the mass budget for the period 1986-1991 to be between +0.22 m and -0.23 m w.e. a^{-1}. Agarwal et al. (2016) reported a mass budget of –0.03 ± 0.21 m w.e. a^{-1} of Siachen Glacier for the period 1999 and 2007. Herreid et al. (2015) found no significant change in debris-coverage of the glaciers in the Hispar and Shimshal sub-regions of the Hunza River basin for the period 1977 until 2014 and concluded that this might be due to balanced glacier budgets during this period. Temperature measurements that are available since 1961 in the Karakoram show, in contrast to many other regions of the globe, a consistent decline in summer and an increase during winter (Fowler and Archer, 2006). Hence, these measurements would support the assumption that glaciers would be in ~~balanced~~balance or slightly positive conditions over the last several decades of the 20th century.

Declassified stereo satellite images from the 1960s and 1970s such as Corona KH-4 and Hexagon KH-9 have been proven to be suitable to generate digital terrain models (DTMs) and assess glacier mass changes since the 1960s (Bolch et al., 2008; Pieczonka et al., 2013~~).~~, Maurer et al., 2016). Hence, the aim of this study is to revisit existing information and extend the time series back to some of the earliest available satellite imagery. We focus on the Hunza catchment in the Central Karakoram (Figure 1) where high heterogeneity of glacier behaviour was found in previous studies (e.g. Bolch et al., 2012; Quincey and Luckman, 2014). Moreover, suitable Hexagon KH-9 data from the 1970s and recent stereo data from ~~~2010~~2009 such as ASTER and Cartosat-1 data were available. The Hunza River is a tributary to the Gilgit River, which flows into the upper Indus. The area of the basin is about 13,715 km² and approximately 25% of the basin is covered by glaciers. These glaciers constitute more than 15% of the glacierized area of the entire Karakoram. Frequent surges reported for several glaciers in this basin (Quincey and Luckman, 2014; Copland et al., 2011; Rankl et al., 2014) complicate the analysis of mass budgets as often only a certain part of a surge is captured.

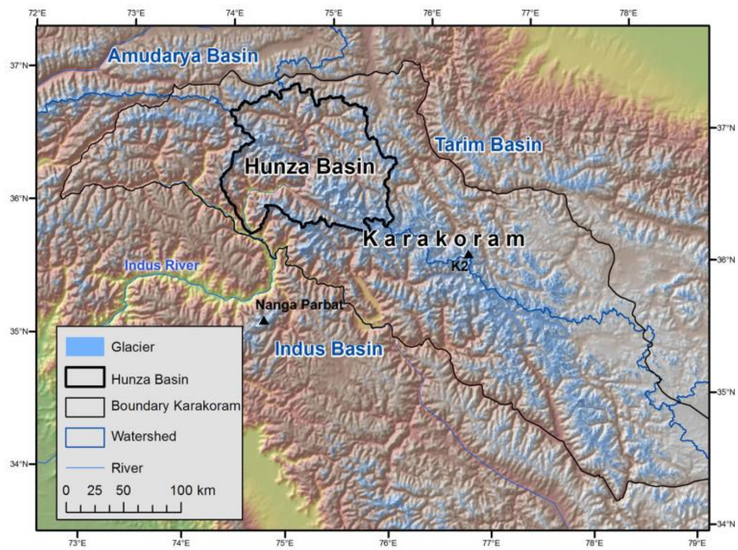

Figure 1: Overview map of the study region.

2. Data and Methods

2.1 Data

The SRTM digital terrain model (DTM) version 4, with a spatial resolution of 1 arc second (~~~30m~~30 m, SRTM1) was utilized as reference dataset. The SRTM1 DTM was acquired by the use of two C-Band radar antennas (operating in interferometric mode) during 11 - 22 February 2000 and is frequently used for glaciological investigations. It can be assumed that the represented ice surface of the ablation region is close to the surface at the end of the 1999 ablation period, assuming a full penetration of the radar beam into snow (Paul and Haeberli, 2008). However, deeper radar penetration can be expected in the accumulation region (Berthier et al., 2006). Data voids which are mainly restricted to some accumulation areas were filled with ASTER GDEM2 data (see section 3.2).

This DTM is a merge of several ASTER scenes covering the period ~2000 – 2010 (Slater et al., 2011). We used ten on demand generated ASTER DTMs (product AST14DEM) from five different acquisition dates of the year 2008~~-~~ – 2010. A small missing ~~stripe~~strip was filled with a DTM from 2013 scenes (Table S1, Fig. S1). ASTER scenes were visually checked and from the most promising available (~~no clouds~~close to end of ablation season, minimum snow cover, no clouds) the respective DTMs were ordered and used for DTM differencing.

~~To estimate rates of elevation change, an acquisition year was assigned for each glacier. We used the mean time difference for glaciers covered by two scenes acquired in different years (Table S3).~~ Two high-resolution Cartosat-1 stereo scenes captured on 11 July 2010 (Table 1) were used to compare and investigate the consistency of the results obtained with the lower resolution ASTER DTM. Cartosat-1 (IRS-P5) was launched by Indian Space Research Organisation (ISRO) in May 2005. The satellite has two high resolution (2.5 m) panchromatic sensors recording stereo images along the track (Titarov, 2008). The major advantage of this dataset, besides the high spatial resolution, is the 12 bit radiometric resolution. Unfortunately, the spatial coverage is relatively small (25 x 25 km) and our two stereo pairs cover only one large glacier (Khurdopin Glacier, glacier nr. 6 in Figure 2) in full.

Declassified Hexagon KH-9 imagery which has a ground resolution of about 8 m and a coverage of about 250 x 125 km allowed us to extend the time series back to 1973 (Table S1). The KH9-Hexagon mission was part of the US keyhole reconnaissance satellite program whose images were declassified in 2002. Imagery from this program have already been applied to investigate glacier mass changes (e.g. Pieczonka et al., 2013).

The ICIMOD glacier inventory (Bajracharya and Shrestha, 2011), also available through the GLIMS database (www.glims.org), was used as a baseline data set and was manually adjusted based on the utilized optical ~~imagery~~imageries for DTM generation and Landsat ETM+ scenes of the years 2000 and 2001.

2.2 DTM generation, postprocessing, differencing and uncertainty

All KH-9 DTMs were generated with Erdas Imagine 2014 Photogrammetry Suite using the frame camera model with a focal length of 30.5 cm. Image pre-processing includes the elimination of internal distortions based on the regularly distributed réseau crosses (originally included to correct film distortion effects) and their removal thereafter, following Pieczonka et al. (2013). GCPs were collected from Landsat 7 ETM+ imagery with SRTM1 as a vertical reference (Pieczonka et al., 2013). Though GCP collection in rough terrain is challenging, we were able to identify 26/28 GCPs (Table S2) located at mountain peaks, large terrain features, and bridges. GCPs were distributed throughout the scenes and at different elevations.

Fiducials were measured manually considering the principal point in the image centre. All stereo images have been processed with a RMS of <~1.5 pixels (Table S2). The final Hexagon KH-9 DTMs cover the entire Hunza basin. A small gap of about 20 pixels exists between the two generated DTMs.

The Cartosat-1 stereo pairs have also been processed using PCI Orthoengine 2014 with 32 and 35 GCPs. To improve the quality of the DTMs, image enhancement techniques were applied prior to DTM generation in order to overcome low image contrast and temporal differences in image acquisition. The root mean squared error (RSME) varied between 0.3 and 3.9 pixels (Table S2). The spatial resolution of all DTMs was chosen as 30 m.

In order to obtain reliable results on glacier surface elevation changes, the DTMs must be properly co-registered (Nuth and Kääb, 2011). As we observed tilts when differencing the original DTMs, we first minimized elevation differences between the different DTMs with respect to the SRTM1 master DTM by applying a first order trend correction. We considered only elevation differences (Δh) between ±150m over non-glacierized terrain with slopes less than 15° (Bolch et al., 2008; Pieczonka et al., 2013). Subsequently, all DTMs were further co-registered following the approach by Nuth and Kääb

(2011). The final ~~displacement~~horizontal shift between all DTMs and SRTM1 were less than or equal to one pixel (≤30 m) on average.

~~Each individual~~To calculate surface elevation changes, we subtract each older ~~co-registered~~ DTM ~~was then subtracted~~ from ~~the~~ more recent DTM~~. The~~ , and mosaic the difference grids ~~were finally mosaicked~~ to facilitate processing. ~~We used~~Where the ASTER DTMs from different time periods overlapped, we calculate a weighted mean elevation change~~,~~ based on ~~area~~the time of acquisition and glacier coverage~~, for the overlapping ASTER DTMs (Fig.~~ (Figure S1~~).~~ , Table S3).

Data voids and mismatches that result in incorrect elevation values can occur in areas with low image contrast such as cast shadows and bright snow. Mismatches due to snow in the accumulation regions led ~~often~~ to unrealistic low elevation values using KH-9 data that would subsequently lead to unrealistic surface lowering values in parts of the accumulation region (Pieczonka and Bolch, 2015). However, thickness change distributions for glaciers with negative mass budgets typically have a minimum lowering at the glacier head with increasing values towards the glacier front following a non-linear trend (Huss et al., 2010). This pattern is different for surging glaciers that often exhibit high positive Δh values at comparatively low elevations, strong surface lowering around the ELA, and then decreasing Δh values towards the upper reaches (Gardelle et al. 2013, Rankl and Braun, 2016). Elevation change patterns can also be affected by thick debris cover where the highest lowering usually does not occur close to the terminus but upstream (Bolch et al., 2008).

As both debris-covered glaciers and surge-type glaciers are common in the investigated region we could not apply a general threshold to remove Δh outliers, but used the general assumption that lower elevations show stronger Δh variability than higher elevations. This should still be true for surging glaciers and those with balanced conditions. The related calculations followed the approach by Pieczonka and Bolch (2015) and used a sigmoid function allowing a larger range of Δh values in the middle part of the ablation region to preserve the signal of surging glaciers and a narrower range (-20≤Δh≤20 m) at the glacier head. We filled all data gaps (including the gap between the two KH9 DTMs) by means of ordinary kriging in order to get the weighted moving average based on neighbouring pixel values.

The penetration of the radar beams into firn and snow has to be considered in case of the comparison of DTMs generated from microwave data such as the SRTM1. However, the value can only be estimated as it depends on several unknown parameters (e.g. snow depth and characteristics) and is therefore one major source of uncertainty (Kääb et al., 2015; Gardelle et al., 2013). We applied ~~the~~a penetration correction of 2.4 ±1.4 m as a mean average. This value was suggested by Kääb et al. (2012), who analysed the beam penetration of the C-band SRTM data in a similar region of the Karakoram ~~and found a penetration of 2.4 ±1.4 m.~~. The conversion of volume to mass changes needs to consider the combined ice and snow density. As both are unknown, we used a density of 850 ±60 kg/m³ as a reasonable and widely used assumption for a longer time period (Huss, 2013).

There is no best method to estimate the uncertainty (e) of the ~~DEM~~DTM differencing when no precise and well distributed GCPs are available. ~~A first estimate provides the~~The standard deviation of the non-glacierized terrain ~~which~~ can serve as a first estimate of the uncertainty and is 22m for the difference between the KH9 and the SRTM ~~DEM~~DTM, 24 m (SRTM~~-~~ - ASTER ~~DEM~~DTM), and 26 m (KH9~~-~~ - ASTER ~~DEM~~DTM). However, the standard deviation can be significantly higher than the real uncertainty as the spatial correlation is not considered (Rolstad et al., 2009). Therefore, we followed the widely applied approach developed by Gardelle et al., (2013):

$$E_{\Delta h} = \frac{E_{\Delta h_i}}{\sqrt{N_{eff}}} \qquad (1)$$

where $E\Delta hi$ is the standard deviation of the mean elevation change of the non-glacierized terrain of each altitude band and *Neff* is the effective number of observations. The latter is calculated using the total number of observations *Ntot*, the pixel size *R* (30 m), and *d* ~~is~~, the distance of spatial autocorrelation of the elevation change maps (1025 m)

$$N_{eff} = \frac{N_{tot} \cdot R}{2d} \qquad (2)$$

The overall uncertainty of the ~~DEM~~DTM difference is the average of $E_{\Delta h}$ weighted by the glacier hypsometry. A further uncertainty to be considered is the uncertainty of the mapped area of the glaciers E_a. We assume an uncertainty of 5% which is towards the upper bound of published estimates of the uncertainty of mapped glaciers based on similar satellite data (e.g. Paul et al. 2013) taken into consideration that the delineation of debris-covered and avalanche-fed glaciers which are both common in the study region is more difficult. The final uncertainty (*E*) is calculated considering also the uncertainty of the radar penetration (E_p, ±1.4 m) and of the volume to mass conversion (E_m, ±7% of the elevation change~~).~~):

$$E = E_{\Delta h} + E_a + E_p + E_m \qquad (3)$$

We did not apply a seasonality correction as most of the images were acquired close to the end of the ablation period but assume the effect is well within the considered uncertainty.

3. Results and Discussion

3.1 Glacier volume and mass changes, surge-type glaciers

Results for the period 1999 to ~2009 show heterogeneous glacier behaviour, with several surging glaciers in the study region (Figure 2). A northern tributary of Hispar Glacier thickened by approximately 150 m at the confluence of the glaciers. Khurdopin and its neighbouring glaciers in south-eastern Shimshal Valley both show significant thickening and thinning within their tongues which is typical of a surge occurring during the study period (Figure 2). In contrast, the large debris-covered Batura Glacier west of Shimshal Valley showed surface lowering throughout the tongue leading to an overall volume loss (Figures 2, 3). For the entire study region we found no significant mass changes (Table 1) which is in line with previous results for the period after 1999 in Central Karakoram (e.g. Gardelle et al., 2013). In addition, we add information

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for glaciers east of their study region (e.g. Batura Glacier) and cover the entire Hispar Glacier, one of the largest glaciers (length 50 km) in the Karakoram. For this region we cannot confirm positive mass budgets but our study indicates a slight mass loss similar to Rankl and Braun (2016) and Kääb et al. (2015). However, our uncertainties are larger due to the utilization of the lower resolution~~, but freely available,~~ ASTER DTM. In addition, we emphasize that the analysed glaciers and period slightly differ which could be a reason for the (not significant) differences to the existing studies.

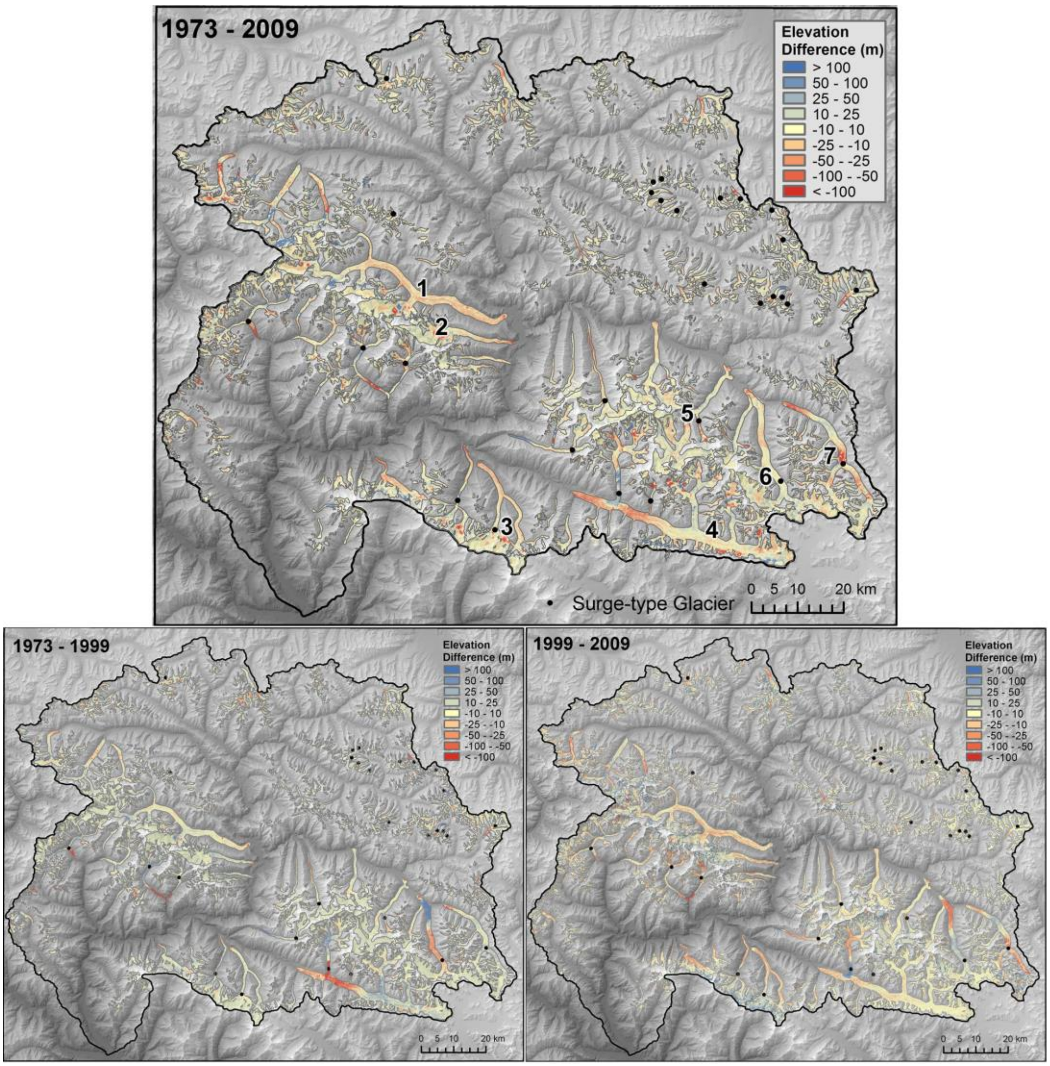


Figure 2: Elevation difference between the ASTER and Hexagon KH9 DTMs (above), the Hexagon KH-9 and the SRTM1 DTMs (below, left) and the SRTM1 and ASTER DTMs (below, right). Black dots indicate surge-type glaciers, the numbers selected larger glaciers: 1: Batura, 2: Pasu, 3: Barpu, 4: Hispar, 5: Yazghil, 6: Khurdopin, 7: Vijerab

Our extended time series ~~show that~~ indicates on average balanced budgets of the glaciers in Hunza Valley ~~experienced no significant mass changes but a heterogeneous behaviour also~~ for the period 1973 to 1999 and slight, but insignificant mass loss for 1999 to ~2009. Heterogeneous behaviour was found in both periods (Table 1). ~~Hence, central Karakoram glaciers were, on average, in balance for~~ Differencing of the 1973 KH9 and ~2009 ASTER DTMs confirm the results of the individual periods without the uncertain penetration correction and reveal slight, insignificant mass loss during at least the last 40 years. ~~Although longer~~Longer-term balanced budgets ~~could be~~had been assumed previously based on existing information about (insignificant) area changes since the 1970s (Bhambri et al., 2013), on average similar debris coverage since 1977 (Herreid et al., 2015~~), we~~). Our results, based on Hexagon KH-9, SRTM and ASTER data, confirm ~~for~~ previous studies and also the ~~first time~~work of Zhou et al. (2017) who found on average balanced-budgets ~~since~~or only a slight mass loss for Central Karakoram between 1973 ~~using elevation differencing~~and 2000.

Most glaciers experienced similar mass budgets for both investigation periods. However, it seems that some glaciers had more negative budgets post-2000. This is especially true for the debris-covered Batura Glacier whose tongue showed significant lowering during 1999 – 2009. Over the entire study period there is no significant difference in the mass budgets of surge-type and non-surge-type glaciers, a result also found by Gardelle et al. ~~-2009. Surge~~(2013) and surge-type glaciers also showed more negative values in the recent period. Kurdophin Glacier, for example, experienced a significant thickening near the snout and a significant lowering around the ELA, both combined resulting in an about zero mass budget for 1973 and 1999 and significant lowering at the lower part of the tongue leading probably to a mass loss for 1999 – 2009 (Figures 2, 3).

For the recent period, the westernmost tributary of Hispar Glacier shows a clear sign of surging with significant elevation gain of more than 100 m at the confluence with the main glacier. This tributary also clearly thickened in the middle reaches during the earlier period (Figure 2). These elevation change characteristics ~~could be~~are likely due to the fact that the ice builds up in the reservoir area during the quiescent phase and the active surge event ~~transferred~~transfers ice mass to lower elevations where it is ~~now~~then more prone to melting. The very high surface lowering ~~of~~rates observed in the middle part of the tongue of Hispar Glacier hints also to a past surge event. It is therefore important to cover the entire surge cycle of surge-type glaciers in order to have valid estimates of their mass budgets. This is the case for most of the glaciers in our study region as we cover a period of almost 40 years and the surge periodicity in the Karakoram is rather short with averages between ~25 and 40 years (Copland et al. 2011). ~~For the recent period, different tributaries of Hispar Glacier showclear signs of surging with significant elevation gains (Figure 2).~~ Overall, we identified 28 surge-type glaciers (including 5 tributaries) based on the DTM differencing results in combination with morphological features like looped moraines or heavily crevassed glacier surfaces (~~Fig. 2). We cannot exclude the possibility that a few surge-type glaciers were missed. However, most of the surge events should be covered by our study period of almost 40 years as~~Figure 2). ~~the surge periodicity in the Karakoram is rather short with averages between ~25 and 40 years (Copland et al. 2011). Over the entire study period there is no significant difference in the mass budgets of surge-type and non-surge-type glaciers, a result also found by Gardelle et al. (2013).~~

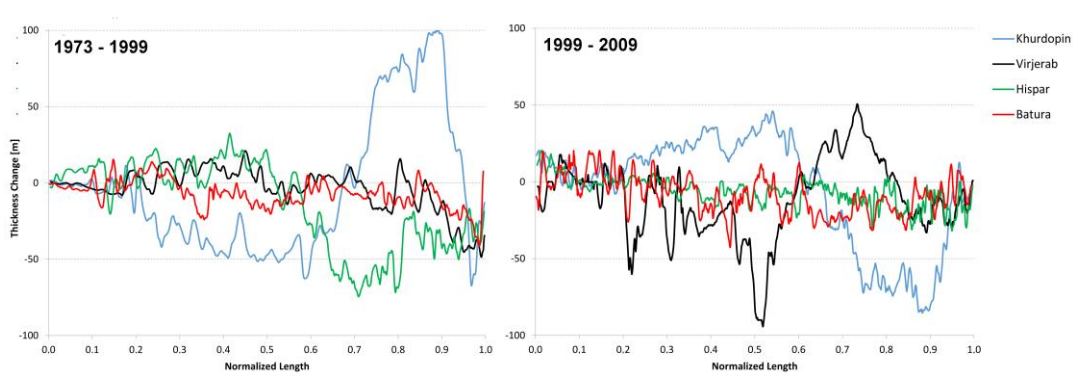
Table 1: Glacier mass ~~balance~~budget for different periods and glacier types

Nr.	Glacier Name	Glacier Type	Area (km²)	Glacier Mass ~~Balance~~Budget (m w.e. a^{-1})		
				1973 - 1999	1999 – ca. 2009	1973 – ca. 2009
1	Batura	Debris covered	236	0.00 ± 0.10	-0.39 ± 0.26	-0.12 ± 0.09
2	Pasu	Debris free	51	+0.05 ± 0.11	-0.13 ± 0.26	-0.09 ± 0.10
3	Barpu	Surge type	90	+0.03 ± 0.08	-0.10 ± 0.18	-0.15 ± 0.08
4	Hispar	Surge-type Debris covered	345	-0.10 ± 0.08	-0.11 ± 0.21	-0.14 ± 0.08
5	Yazghil	Debris covered	99	-0.02 ± 0.13	-0.04 ± 0.32	-0.01 ± 0.12
6	Khurdopin	Surge-type Debris covered	115	-0.05 ± 0.09	-0.14 ± 0.22	-0.05 ± 0.08
7	Vijerab	Surge-type Debris covered	113	+0.03 ± 0.10	-0.31 ± 0.25	-0.22 ± 0.09
	Whole region		**2868**	**-0.01±0.09**	**-0.08 ± 0.21**	-0.06 ± 0.08
	Whole region	Non-surge-type	2237	0.00 ± 0.08	-0.03 ± 0.22	-0.03± 0.08
	Whole region	Surge-type	631	-0.03 ± 0.10	-0.15 ± 0.30	-0.09 ± 0.09

3.2 DTM generation and sources of uncertainty

Declassified KH-9 Hexagon data have been proven to be valuable for assessing geodetic glacier mass budgets (Pieczonka and Bolch, 2015; Pieczonka et al., 2013, ~~Mauer~~Maurer et al. 2016). The main challenges in obtaining accurate results are miscorrelations in the accumulation regions of glaciers and significant tilts and shifts of elevation trends making careful co-registration and post-processing necessary. This leads to higher uncertainties compared to more recent data with a similar spatial resolution. The glacier volume changes calculated based on the automatically derived ASTER DTMs (AST14DEM) and the SRTM DTM were similar to those using better quality higher resolution SPOT5 DTMs for a similar region (Gardelle et al., 2013). ~~The~~Off-glacier DTM differences ~~between the utilized DTMs of the off-glacier area shows the in general~~show good agreement in general, but also regions with higher deviations ~~especially for the western part~~ where the quality of the ASTER ~~DEMs~~DTMs were lower (e.g. the western part of the study areas, Fig. S1). We found no significant difference between the mass budget results of Khurdopin Glacier calculated using Cartosat-1 data and the values calculated using the ASTER data (-0.14 ± 0.21 for 1999~~-~~ – 2009 vs. -0.16 ± 0.13 for 1999 – 2010). This gives confidence that the ASTER DTMs which can be freely obtained for scientific purposes are of high value to calculate glacier volume and mass changes over a longer period of time as also shown for other regions (e.g. Berthier et al., 2016).

A further source of uncertainty are the data voids in the original SRTM data and voids due to the outlier filtering. About 20% of the total glacierized area for all analysed periods were identified as outliers and filled afterward by kriging interpolation. The voids are almost entirely located in the accumulation region where surface elevation changes are relatively small (e.g. Schwitter & Raymond, 1993) and where we restricted the maximum possible deviation. To assess the influence of the filling on the result we calculated the elevation change value for the whole basin and the period 1973 – 2009 (a) without void filling (result: mean elevation difference -3.80 m or -0.09 m w.e. a^{-1}), (b) filling with zero (-2.98 m or -0.07 m w.e. a^{-1}), or (c) our applied interpolation method (-2.39 m or -0.06 m w.e. a^{-1}). The results show that average elevation change rates do not change significantly and the deviations are well within the uncertainty. About 10% of the glacierized area in our study region is affected by data voids in the original SRTM data and previous studies showed that there can be significant deviations to reality in the data used to fill the voids (e.g. Kääb et al. 2012). In addition, the time stamp of the data is often unknown. We compared therefore the results of the void filled and the non-void filled version. Using the latter we calculated the surface elevation change for the existing pixels only. The resultant value of the mean surface elevation change for both periods differs only by about 0.02 m a^{-1}, which is also well within the estimated uncertainty. The minor differences are, besides the possibility that the ASTER GDEM data used for void filling are quite reliable for the study region, due to the fact that most of the voids are located in the accumulation regions where we restricted the maximum possible deviation. Only one larger glacier is also affected in the ablation region. This is Shishpar Glacier, a southerly facing exposed glacier, located south of Batura Glacier. The void-filled data allowed for detection of the surge activity between 1973 and 1999 with an estimated mass budget of +0.04 ± 0.19 m w.e. a^{-1}.



~~**Figure 3: Longitudinal profiles of surface elevation changes for selected glaciers for the two periods.**~~

One of the major sources of uncertainty is the penetration of the radar beam into snow and ice when using the SRTM DTM. Gardelle et al. (2013) estimated a mean penetration of 3.4 m with values up to more than 9 m in the accumulation region. This value is higher than the 2.4 m we applied here following Kääb et al. (2012). However, applying the higher penetration value would only lead to a slight difference in mass change of ~~+~~±0.03 m w.e. a^{-1}. The average surface elevation change without considering any radar penetration is -0.10 m a^{-1} for the period 1973~~-~~ – 1999 and +0.15 m a^{-1} for the period 1999~~-~~ – 2009.~~–~~ However, penetration is not an issue for calculation of the geodetic mass budget over the entire period (~1973~~-~~ – 2009) as this uses optical data only. As the results of the individual periods are in good agreement with the values for the entire period, we are confident in the reliability of all mass ~~balance~~budget calculations.

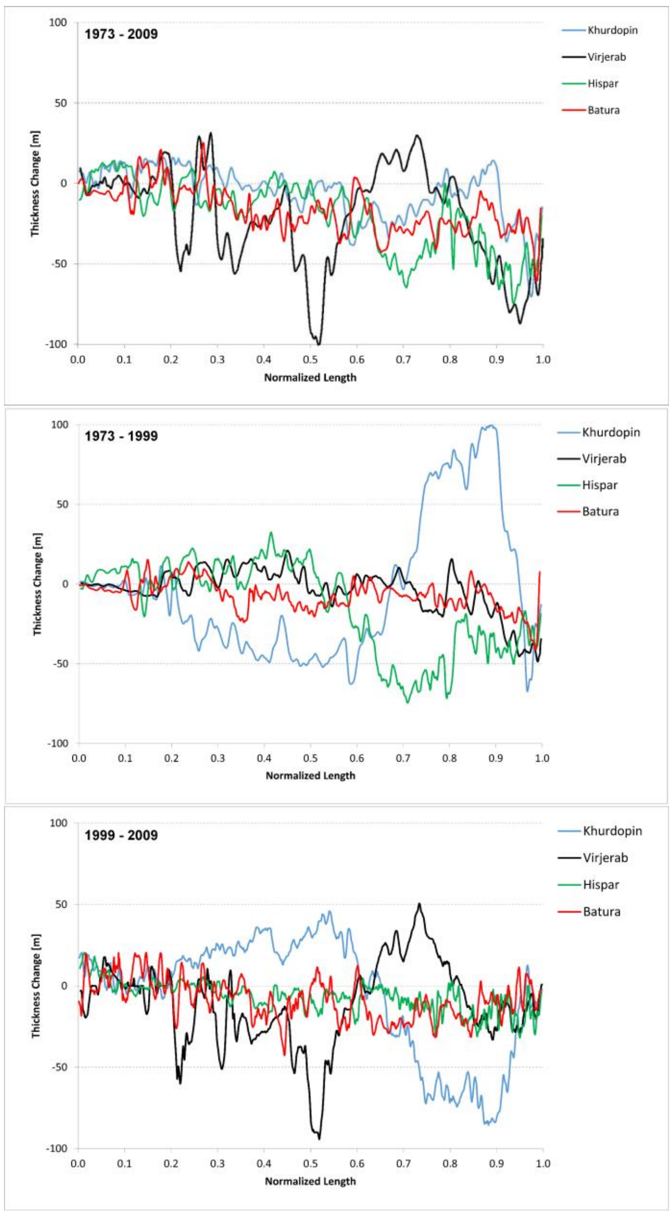

1973 - 2009
Khurdopin
Virjerab
Hispar
Batura
Thickness Change [m]
Normalized Length
1973 - 1999
Khurdopin
Virjerab
Hispar
Batura
Thickness Change [m]
Normalized Length
1999 - 2009
Khurdopin
Virjerab
Hispar
Batura
Thickness Change [m]
Normalized Length

Figure 3: Longitudinal profiles of surface elevation changes for selected glaciers for the entire period (1973 – 2009) and the subperiods 1973 – 1999 and 1999 – 2009 periods.

4 Conclusion

~~Although longer term balanced budgets in the Karakoram region could be assumed based on existing information, such as insignificant changes in glacier area or debris-covered area since the 1970s, we confirm~~ We showed based on 1973 Hexagon, SRTM and ~2009 ASTER ~~DEM~~DTM data that heterogeneous behaviour and close to balanced-budgets in the investigated region in Hunza Valley (Karakoram) are not a recent phenomenon. Since at least the 1970s, glaciers in the ~~Hunza~~study region have experienced on average ~~no significant~~ only a slight, insignificant overall mass ~~changes. This is important information as glacier area and length changes represent an indirect~~loss. However, significant differences can exist for individual glaciers for the two investigated periods 1973 – 1999 and ~~delayed response to climate~~1999 – 2009. Especially surge-type glaciers show different elevation change characteristics and ~~deriving a clear cause and effect relation is difficult to establish. On the other hand, during~~more negative mass budgets in the second period. During a surge, ice is transported rapidly from an upper reservoir zone to the ablation region and ~~vice versa during the quiescent phase, albeit on an often much longer time scale.~~is prone to melt at the lower elevations. With the almost 40-year time-period considered here ~~it was possible to~~ we show that the overall mass change ~~remains about the same but that significant differences exist for individual glaciers~~of surge-type glaciers and non-surge-type are not significantly different when the entire surge cycle is considered. However, further long-term mass budgets studies are needed to confirm these findings.

Author Contributions

T.B. designed the study, performed all analysis, generated the figures and wrote the draft of the manuscript. K.M. generated the raw Hexagon and Cartosat-1 DTMs and co-registered the data. T.B. and T.P. supported the generation of the DTMs and the co-registration. J.S. contributed to the study design, and all authors contributed to the final form of the article.

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Brief Communication: ~~Glaciers~~Nearly balanced glaciers in the Hunza Catchment (Karakoram) ~~are in balance~~ since the 1970s

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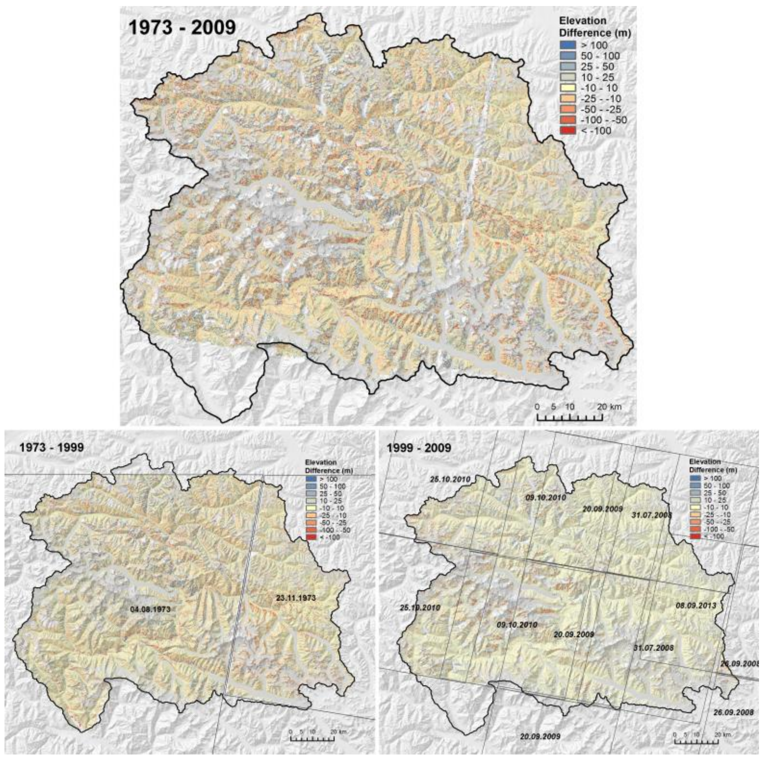
Supplementary Material

Supplementary ~~figures~~figure


1973 - 2009
Elevation Difference (m)
> 100
50 - 100
25 - 50
10 - 25
-10 - 10
-25 - -10
-50 - -25
-100 - -50
< -100
0 5 10 20 km
1973 - 1999
04.08.1973
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1999 - 2009
25.10.2010
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20.09.2009
08.09.2013
31.07.2008
26.09.2008

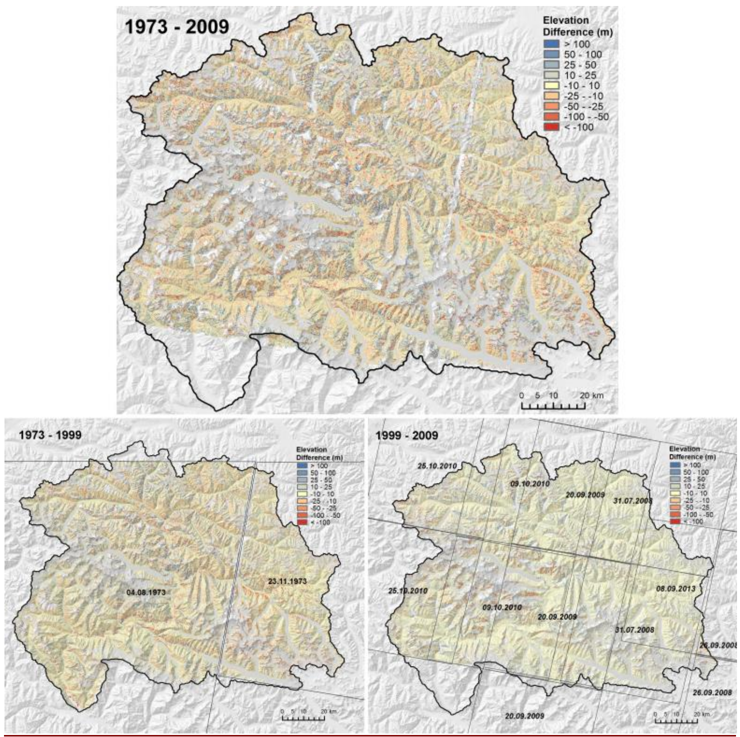

Figure S1: Elevation differences of the off glacier area between the ASTER and Hexagon KH9 DTMs (above), the KH9 and SRTM DTMs (below, left) and the SRTM and ASTER DTM (below, right). The figure includes the coverage and the acquisition date of the images used for DTM generation of the different tiles.

Supplementary tables

Table S1: List of utilized satellite images

Date(s)	Sensor/Data	ID	Spatial Resolution	Purpose
04/08/1973 04/08/1973	Hexagon KH-9	DZB1206-500082L020001 DZB1206-500082L021001	~8m	Glacier mapping, DEM generation, DEM differencing
23/11/1973 23/11/1973 23/11/1973	Hexagon KH-9	DZB1207-500045l005001 DZB1207-500045l006001 DZB1207-500045l007001	~8m	Glacier mapping, DEM generation, DEM differencing
Feb. 2000	SRTM 1		30m	DEM differencing
25/10/2010	ASTER	AST14DEM_00310252010055219_20140122060824_29130	30m	DEM differencing,

	14DEM			glacier mapping
25/10/2010	ASTER 14DEM	AST14DEM_00300000000000000_20140122060834_29176	30m	DEM differencing, glacier mapping
09/10/2010	ASTER 14DEM	AST14DEM_00300000000000000_20140219133734_23637	30m	DEM differencing, glacier mapping
09/10/2010	ASTER 14DEM	AST14DEM_00310092010055216_20140219133724_23540	30m	DEM differencing, glacier mapping
20/09/2009	ASTER 14DEM	AST14DEM_00300000000000000_20140219133724_23558	30m	DEM differencing, glacier mapping
20/09/2009	ASTER 14DEM	AST14DEM_00300000000000000_20140219133724_23534	30m	DEM differencing, glacier mapping
31/07/2008	ASTER 14DEM	AST14DEM_00307312008055349_20140219133743_23680	30m	DEM differencing, glacier mapping
31/07/2008	ASTER 14DEM	AST14DEM_00307312008055349_20131210035721_12481	30m	DEM differencing, glacier mapping
26/09/2008	ASTER 14DEM	AST14DEM_00300000000000000_20140219133733_23639	30m	DEM differencing, glacier mapping
26/09/2008	ASTER 14DEM	AST14DEM_00300000000000000_20140219133734_23643	30m	DEM differencing, glacier mapping
08/09/2013	ASTER 14DEM	AST14DEM_00309082013054614_20140219133734_23638	30m	DEM differencing
11/07/2010	Cartosat-1	505/231	2.5m	DEM-generation DEM differencing
11/07/2010	Cartosat-1	505/232	2.5m	DEM-generation DEM differencing

Table S2: Number of used GCPs and their RSME after triangulation for KH9 and Cartosat-1 stereo image processing using Imagine Photogrammetry

	No. of GCPs	RMSE (Pixel)
KH9	26	1.29
KH9	28	1.4
Cartosat-1	32	3.91
Cartosat-1	35	0.33

Table S3: Used ASTER DTMs for the selected glaciers and weighted mean of time difference between DTMs used for calculating difference rates considering the acquisition date and the glacier coverage.

Glacier	Dates ASTER DTMs ~~used~~	Time difference ASTER – SRTM ~~(wighted~~data (weighted mean)	Time difference ASTER – KH9 data (weighted mean)
Batura	09.10.2010/02.09.2009	10.8 years	36.8 years
Pasu	09.10.2010/02.09.2009	10.5 years	36.5 years
Barpu	09.10.2010/02.09.2009	10.5 years	36.5 years
Hispar	31.07.2008/02.09.2009	9.2 years	35.2 years
Yazghil	31.07.2008	9 years	35 years
Khurdopin	31.07.2008	9 years	35 years
Vijerab	31.07.2008/26.09.2008/08.09.2013	9.2 years	35.2 years
Whole region	Mean ca. 2009	10.1 years	36.1 years

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