Dear Editor,

We have carefully revised the manuscript taking the reviewers comments into account. We followed most of the comments. In case we, disagree we explained why. The most important comment which were also raised by you was that we did not calculate the mass changes for the entire period 1973 – ca. 2009. We did now carefully and the results confirm our previous estimates. Please see our detailed reply below. 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

Reply to comments from Reviewer #1
The comments are repeated in *italic*, our reply is given in **bold**.

This study utilizes digital elevation models extracted from satellite imagery (historical Hexagon and modern SRTM and ASTER) to calculate a regional geodetic mass balance for glaciers in the Hunza River basin, Karakoram region, using DEM differencing. The authors show that given the uncertainties of the methodology, the regional geodetic mass balance is not statistically different from zero change, consistent with previous mass balance studies on shorter more recent timescales. Their results suggest that the so-called "Karakoram anomaly" is not limited to the past _15 years, but extends back to at least 1973. This is the first study using elevation differences to confirm this finding over a several-decade timespan, which supports previous studies showing no significant changes in debris cover or glacier area in the Karakoram over similar (1970's-present) time periods. Overall, it is a nice paper, and is ready for publication after a few minor additions.

Reply: Thank you.

A table of values showing the standard deviation of mean elevation change between the ASTER and SRTM DEMs for assumed stable (non-glacier) terrain is needed to better assess the relative vertical accuracy of the DEMs.

Reply: We included an established uncertainty assessment for estimate the accuracy of the results. These results are assigned as uncertainty range to each resultant number and given in Table 1. We now also include information about the standard deviation of the elevation difference between the final ASTER DEM and the SRTM DEM, and also the differences between in the KH-9 and ASTER and KH-9 and SRTM DEMs in the manuscript.

Regarding the satellite imagery datasets, a paragraph, table, or figure to clearly show which DEMs are being subtracted from one another for each given time period, i.e. SRTM minus Hexagon for 1973-1999, and ASTER minus SRTM for 1999-2009. This would serve the clarify the methods section significantly.

Reply: There is a figure in the supplementary material which shows the boundaries of the utilized images. There is no overlap of the Hexagon DEMs, hence it is clear which area was subtracted. We agree, however, that this is not so straight forward for the ASTER DEMs. In case an area is covered by more than one DEM, we used the mean of all available DEMs. We clarified this issue in the manuscript and refer now to a new table in the supplement. However, the new numbers only changed at the cm scale, which is well within the uncertainty.

Since the primary motivation of the paper is to extend the geodetic mass balance record further back in time, I would recommend an additional calculation of the full timespan (1973 - 2009) mass balance. This would also serve to validate the 1973-1999 and 1999-2009 mass balances, and remove the significant uncertainty regarding SRTM penetration into the ice.

Reply: We have done so for few glaciers to clarify that the results agree well to the results of the individual periods. We agree, however, that it would be beneficial to also include the DEM difference for the entire period. This is now done for the revised manuscript. In general, the values fit very well so our general statement is still supported by the analysis. However, we detected some deviation for Barpu Glacier. We investigated the potential reason more in detail and found unrealistic high elevation gain in parts of the accumulation region. We therefore adjusted the filtering slightly and the resultant mass balance value changed from -0.03 ± 0.18 to -0.10 ± 0.18. The value 1973-2009 is lower but still falls within the uncertainty of both subperiods. Within our detailed revisions of the calculation of the values for the entire period we got also slightly but insignificantly different values for the individual glaciers. These differences stem mainly from new outlier filtering detailed in the revised manuscript.

The equations used for estimating uncertainty lean toward the more conservative side (i.e. large error bars). For example, linearly adding up the errors in Eq. 3 instead of adding in quadrature, which assumes that the error components in Eq. 3 are completely correlated with one another. The authors should make clear in the conclusion of the manuscript - results show no statistical difference from zero change, given the somewhat large/conservative uncertainties used with the DEM differencing method.
Reply: We understand the concern, but think the uncertainty is more realistic when adding the uncertainties of the radar penetration, volume to mass conversion etc. and considering the error propagation linearly would underestimate the uncertainty from our point of view. This is the same approach used by Gardelle et al. 2013 also provides rather conservative error estimates. However, even with smaller uncertainty estimates the general statement that there we no significant differences between the period before and after 2000 holds true.

Specific comments:

P3 L6 Were any glaciers covered only partially by scenes from different years? If so, it may be best to use a weighted mean (weighted by the percentage of a glacier's area covered by each scene).

Reply: Yes, especially the larger glaciers are covered by more than one scene. We originally used the mean value for the overlapping parts. We now use the weighted mean of all the scenes used for a glaciers considering the area coverage as suggested. However, as stated above the resultant numbers changed only in the third decimal digit which is well within the uncertainty.

P3 L8 It is still somewhat unclear to me how the Cartosat-1 data is being used. I assume the authors compute Cartosat minus SRTM, then compare to ASTER minus SRTM in order to check consistency between the datasets. This should be further clarified in the text.

Reply: Yes, it was done to compare to the ASTER derived which have significant lower resolution. We write now: "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."

P2 L18 "assuming a full penetration of the radar beam into snow..." - regarding the ablation region. What about additional penetration into the ice itself, is this taken into account?
Reply: Yes this is taken into account. We applied the correction suggested by Kääb et al. (2012) who analysed the penetration depth for a similar region.

P2 L20 It would be useful here to refer to the later section (3.2) so the reader can easily find the discussion regarding void filling with the ASTER GDEM2 and associated uncertainties.

Reply: We referred to section 3.2. as suggested.

P3 L24 "All stereo images have been processed with a RMS of < _1.5 pixels." Which aspect of the stereo photogrammetry is this referring to? Is this the reprojection error of triangulated ground control points after bundle adjustment, or something to do with the reseau grid distortion removal, or something else? A more detailed explanation is needed to interpret the meaning.
P3 L28 See previous comment regarding P3 L24

Reply: We refer to the RMSE of the GCPs after triangulation. We improved the caption of Table S2 accordingly.

P3 L32 What kind of spatial trend corrections were made? Rotation, translation, or perhaps polynomial surface corrections... if so are they first order (linear), or higher order polynomials, or some other method?

Reply: We applied a first order trend correction. We will clarify this in the revised manuscript.

P4 L12 Was the outlier threshold applied to both Hexagon and ASTER data, or to Hexagon only? If no outlier filtering was needed for the ASTER DEMs, this should be stated explicitly in the text.
P4 L17 It would be helpful to know the percentage of total pixels excluded (using the outlier threshold filter) for each glacier, to ensure that no large regions were interpolated using the

ordinary kriging; otherwise unrealistic elevations could result. The text later discusses the percentage of voids in the SRTM data, but says nothing regarding the percentage of data gaps in the Hexagon data.
P6 L13 Going back to the previous comments regarding P4 L12 and P4 L17 – Since both time periods use different data sources and therefore contain differing amounts of data voids - a percentage of voids for each would help eliminate doubts regarding direct comparisons between the two time periods, which use SRTM - Hexagon for 1973-1999, and ASTER - SRTM for 1999-2009. Could a difference in data gaps/holes make a significant difference when comparing these datasets/time periods?

Reply: The outliers were filtered for all DEM differences, but it was more important for the DEM differencing using Hexagon data. We have clarified this in the revised manuscript and also provide the information about the resultant voids in the different data sets. The impact of the outlier filtering and the gap filling is now covered in the discussion section.

P6 L11 "we confirm for the first time using elevation differences..." Should specify: over this longer time period (because elevation differences have been used over shorter time periods in previous studies).

Reply: We agree and will now specifically mention “based on 1973 Hexagon and ~2009 ASTER DEMs”.“

P6 L17 What is meant by "different surge stages in the two periods..."? What is different between the two periods regarding surges, the magnitude, timing, or something else? Or is the word "different" simply being used in a fashion equivalent to "separate"?

Reply: We simply meant that, e.g. one period covered the active surge of the glacier while the second probably the quiescent phase. We are now more specific and provide an example.

P8 L1 When calculating the mass budget with the non-void-filled version of SRTM for comparison, were the voids interpolated, or was the mass balance computed using only the volume change of existing pixels, then divided by the glacier area only covered by existing pixels? More details would be helpful.

Reply: We write now: “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”

Technical corrections:

P2 L7 complicate the

Corrected

P3 L10 “The major advantage of this dataset is besides the high spatial resolution and also the 12 bit pixel depth” – strange wording. Should change to something like: “The major advantages of this dataset are the high spatial resolution and 12-bit pixel depth.”

Reply: The sentence was rewritten to: "The major advantage of this dataset is besides the high spatial resolution the 12 bit radiometric resolution."

P7 L11 ": : : ASTER DEMs where lower: : :" change "where" to "were"

Reply: Corrected

P8 L6 voids

Reply: Corrected

P8 L4 versions

Reply: We think the singular is correct here: "We compared therefore the results of the void filled and the non-void filled version."

Reviewer #2
We'd like to thank the reviewer for the constructive review. Please find below our reply to the comments. We will provide a more detailed reply along with the revised manuscript.

RC: This is a useful study that provides the first long-term information (since the 1970s) about geodetic glacier mass balance for a region of the Karakoram. This is a region where many recent papers have suggested that glaciers are changing little in mass, but prior to this study little previous information has been available about glacier elevation changes before _2000. The techniques are well described, the errors are well quantified, and useful final conclusions are produced.
Most of my comments are relatively minor and focused on technical issues, but there are two useful analyses that could be undertaken that would help to strengthen the paper:

1. A computation of the total elevation changes over the period 1973-2009 should be completed. This would help to validate the patterns shown in the individual periods, potentially reduce the effect from individual surges, and provide evidence that mass balance has been stable over the long term.

Reply: As this point was also raised by Reviewer 1, we now examine the total elevation change from 1973 – 2009. In general, the total elevation change over the entire period matches that found for the individual periods, and so our general statement is supported by the analysis. However, we detected some deviation for Barpu Glacier. We investigated the potential reason more in detail and found unrealistic high elevation gain in parts of the accumulation region. We therefore adjusted the filtering slightly and the resultant mass balance value changed from -0.03 ± 0.18 to -0.10 ± 0.18. The value 1973-2009 is lower but fits well within the uncertainty to the sum of both subperiods.

RC: 2. Provide a plot and discussion of the change in geodetic mass balance with altitude for non surge-type glaciers. This could provide insight into whether changes are occurring at particular altitudes, even though the overall mass balance may be close to zero.

Reply: We agree that this information would be valuable. However, there are several other interesting analyses which could be done, e.g. comparison of the elevation change with altitude of debris-covered and non debris-covered glaciers. However, we chose the format of the Short Communication as we wanted to focus on the main new findings. In addition, we cannot add another figure due to the limitations in the chosen format.

Individual comments:

P2, L22: there is actually this mass balance study available for a glacier in the Karakoram prior to 2000, although it only covers a 5 year period: Bhutiyani, M. R. 1999. Mass-balance studies on Siachen Glacier in the Nubra valley, Karakoram Himalaya, India. Journal of Glaciology, 45(149), 112-118.

Reply: Fully agreed, Thank you for this correction.

We will include: "The only exception is 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 to be between +0.22 m and -0.23 m w.e. a^{-1}."

P2, Fig. 1: it would be useful to label the location and names of some of the main peaks or towns in this region to make the map easier to follow. The lat/long labels around the margins are also currently too small to see.

Reply: We agree. We will include the names of few larger villages and known mountain peaks and enlarge the font size of the coordinates

P3, L11: the sentence 'The major advantage: : :' doesn't really make sense as written. Please reword.

Reply: We agree and wrote now: "The major advantage of this dataset is besides the high spatial resolution the 12 bit radiometric resolution.

P3, L13: please provide the resolution and spatial extent of the KH-9 imagery. I also think that you mean to refer to Table S1 here, not Table 1

Reply: We agree and included the information "…which has a ground resolution of about 8 m and a coverage of about 250 x 125 km…" and refer to table 1.

P3, L16: should be 'database' (one word)

Reply: corrected

P31, L21: a few words to explain what the 'reseau grid' is would be useful as it's not a commonly used term. I also think that it should be spelled 'Réseau grid'

Reply: We agree and wrote now:
"Image pre-processing, comprising the elimination of internal distortions based on the réseau crosses regularly distributed crosses on the image which have this purpose to be able correct effects of film distortion) and their removal thereafter, …"

P31, L23: change 'GCPs have been collected: : :' to 'GCPs were collected: : :'. Also describe how and where the GCPs were chosen – e.g., Were they located on bedrock areas? How many were used? Were they chosen across a range of elevations?

Reply: The numbers of the utilized GCPs were listed in Table S2. We included the following information in the manuscript: "GCP collection in rough terrain is challenging. Finally we were able to find 26/28 GCPs located at mountain peaks, large terrain features, and bridges which we distributed throughout the scenes and in different elevations as best as possible."

P5, L5-6: I'm unclear as to why a 5% uncertainty was chosen for the glacier area mapping. If there are good optical satellite images available for this area, then presumably it should be relatively straightforward to map the glacier areas with <5% uncertainty?

Reply: The glaciers are not that straightforward to map as there are several debris-covered ones. The major issue is, however, the correct delineation of the upper glacier boundary as several glaciers are avalanche fed and located below steep slopes where the boundary is not fully clear. Taken this into consideration and the fact that the study by Paul et al. (2013) revealed similar uncertainties in a mapping experiment where different experts provided glacier outlines, we think this estimate of the uncertainty is reasonable.

P6, Fig. 2: I find the labels and dots on these figures quite difficult to see as they're so small. Also please indicate the source of information for identifying which glaciers are surge-type. As mentioned above, it would also be very useful to produce a DEM difference map for the entire study period (1973-2009).

Reply: We increased the size of the labels and dots in the new included figure for the period 1973-2009 and included the information about how we identified the surge-type glaciers in the text of the manuscript ("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 analysed the elevation difference of the entire study period and include the figure in the text.

P7, Table 1: similar to the comment for Fig. 2, please include a column to show the glacier mass balance values for the entire study period 1973-2009.

Reply: We included also the mass balance values for entire study period in table 1.

P7, L11: 'where lower' should be 'were lower'

Reply: corrected

P8, L1-3: the first sentence in this para is difficult to follow. The rest of this para is also quite awkwardly worded, with quite a few typos. Please be sure to check carefully. E.g., L8: change 'allowed to detect the surge activity' to 'allowed for detection of surge activity'. Also – what does 'south exposed glacier' mean? Do you mean southerly facing?

Reply: We agree that some wording were a bit awkward. We improve it in the revised manuscript.

P8, Fig. 3: also show the total change from 1973-2009

We think most interesting for the profile is the difference between the two periods and showing the profiles will not prove important additional information for the selected glaciers. However, it the reviewer insists it is no problem to add. But we will then probably move this figure to the supplement as the length of the manuscript and number of figures is restricted in a short communication.

P9, L7-9: it would be useful to add a few words here (or elsewhere) about the relatively rapid surge periodicity in the Karakoram: i.e., that within a 40 year period it's likely that you've captured a large part of a surge cycle (or even more than one). This is different to locations such as Svalbard, where the active and quiescent phases are typically much longer.

Reply: This is a good point. We include this information now and write "…most of the surge events should be covered by our study period of almost 40 years as the surge periodicity in the Karakoram is rather short with averages between ~25 and 40 years (Copland et al. 2011)."

Figure S1: it's unclear as to which dates refer to which areas, particularly for the 1999-2009 image. Colour coding the date label and associated box would help

Reply: We tried different possibilities to improve clarity, but also colour coding was not really better as several colours would be needed and they would then interfere with the DT difference image. It is possible to identify the dates as they are placed in the middle of the polygons representing the scenes. Therefor we would prefer to leave the figure as it is.

Table S1: indicate what (P/R, K/J) indicate in the header for column 3

Reply: (P/R, K/J) are indeed confusing and not needed. We forgot to delete and will delete for the revised version.

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

Tobias Bolch[1,2], Tino Pieczonka[2], Kriti Mukherjee[2], Joseph Shea[3]

[1]Department of Geography, University of Zurich, 8057 Zurich, Switzerland
[2]Institute for Cartography, Technische Universität Dresden, 01069 Dresden, Germany
[3]International Centre for Mountain Development (ICIMOD), Kathmandu, Nepal

Correspondence to: Tobias Bolch (tobias.bolch@geo.uzh.ch)

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 mass budget analyses are available before 2000. Here, we show that glaciers in the Hunza River basin (Central Karakoram) were on average in balance or showed slight insignificant mass loss ~~since the 1970s~~within the period ~1973 – 2009. ~~based on analysis of stereo Hexagon KH-9, SRTM, ASTER and Cartosat-1 data.~~ 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~~ly~~ glacier mass change rates differed significantly for the periods before and after ~2000. These analyse~~i~~s 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). 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). However, almost no mass budget analyses are available for Karakoram glaciers prior to ~~for the period before~~the year 2000. The only exception is Siachen Glacier in eastern Karakoram, for which Zaman and Liu (2015) corrected the erroneous~~ clearly negative~~ value of -0.51 m w.e. a^{-1} given by~~.~~ Bhutiyani (1999), and estimated the mass budget to be between +~~-~~0.22 m and –~~-~~0.23 m w.e. a^{-1}. 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 or slightly positive conditions over the last several decades of the 20^{th} 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). 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 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.

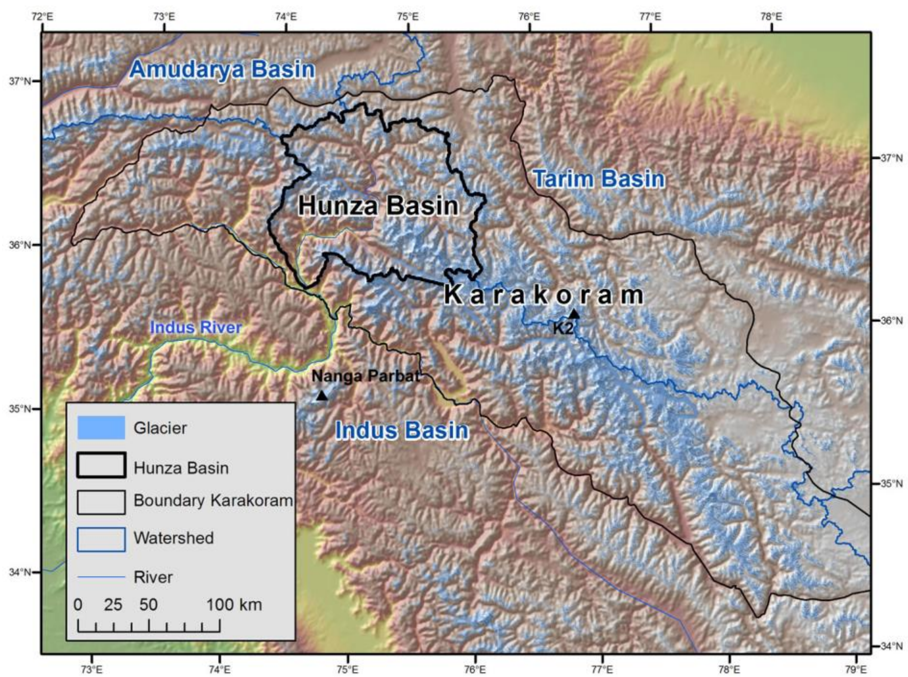

Figure 1: Overview map of the study region

2. Data and Methods

2.1 Data

The SRTM digital terrain model (DTM) version 4, with a spatial resolution of 1 arc second (~30m, 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 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, minimum snow cover) 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~~year~~ 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~~gained~~ 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, ~~is~~ besides the ~~-~~high spatial resolution, is ~~and also~~ the 12 bit radiometric resolution~~.pixel depth~~. 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 data~~-~~base (www.glims.org), was used as a baseline data set and manually adjusted based on the utilized optical imagery 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~~reseau grid removal~~ , ~~has been performed fo~~following Pieczonka et al. (2013). GCPs were~~have been~~ collected from Landsat 7 ETM+ imagery with SRTM1 as a vertical reference (Pieczonka et al., 2013). Though GCP collection in rough terrain is challenging, ~~. Finally~~ we were able to identify ~~find~~ 26/28 GCPs (Table S2) located at mountain peaks, large terrain features, and bridges. GCPs were ~~which we~~ distributed throughout the scenes and at~~in~~ different elevations. ~~as best as possible.~~

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 ~~exists~~.

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 ~~based on spatial~~ trend correction~~s~~. 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 between all DTMs and SRTM1 were less than or equal to one pixel (≤30 m) on average.

Each individual older co-registered DTM was then subtracted from the more recent DTM. The difference grids were finally mosaicked to facilitate processing. We used a ~~the~~ weighted mean elevation change, based on area of coverage, ~~value~~ for the overlapping ASTER DTMs (Fig. S1).

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 ($-20 \leq \Delta h \leq 20$ 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 correction 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 differencing when no precise and well distributed GCPs are available. A first estimate provides the standard deviation of the non-glacierized terrain which can serve as a first estimate and is 22m for the difference between the KH9 and the SRTM DEM, 24 m (SRTM-ASTER DEM), and 26 m (KH9-ASTER DEM). However, the standard deviation can be significantly higher than the real uncertainty as the spatial correlation is not considered (Rolstad et al., 2009). Here,Therefore, we followed the a widely applied approach developed and calculated the uncertainty followingby 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 difference is the average of EΔh 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 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).

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

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 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 ~~want to~~ emphasize that the analysed glaciers and period slightly differ which could be a reason for the (not significant) differences to the existing studies.

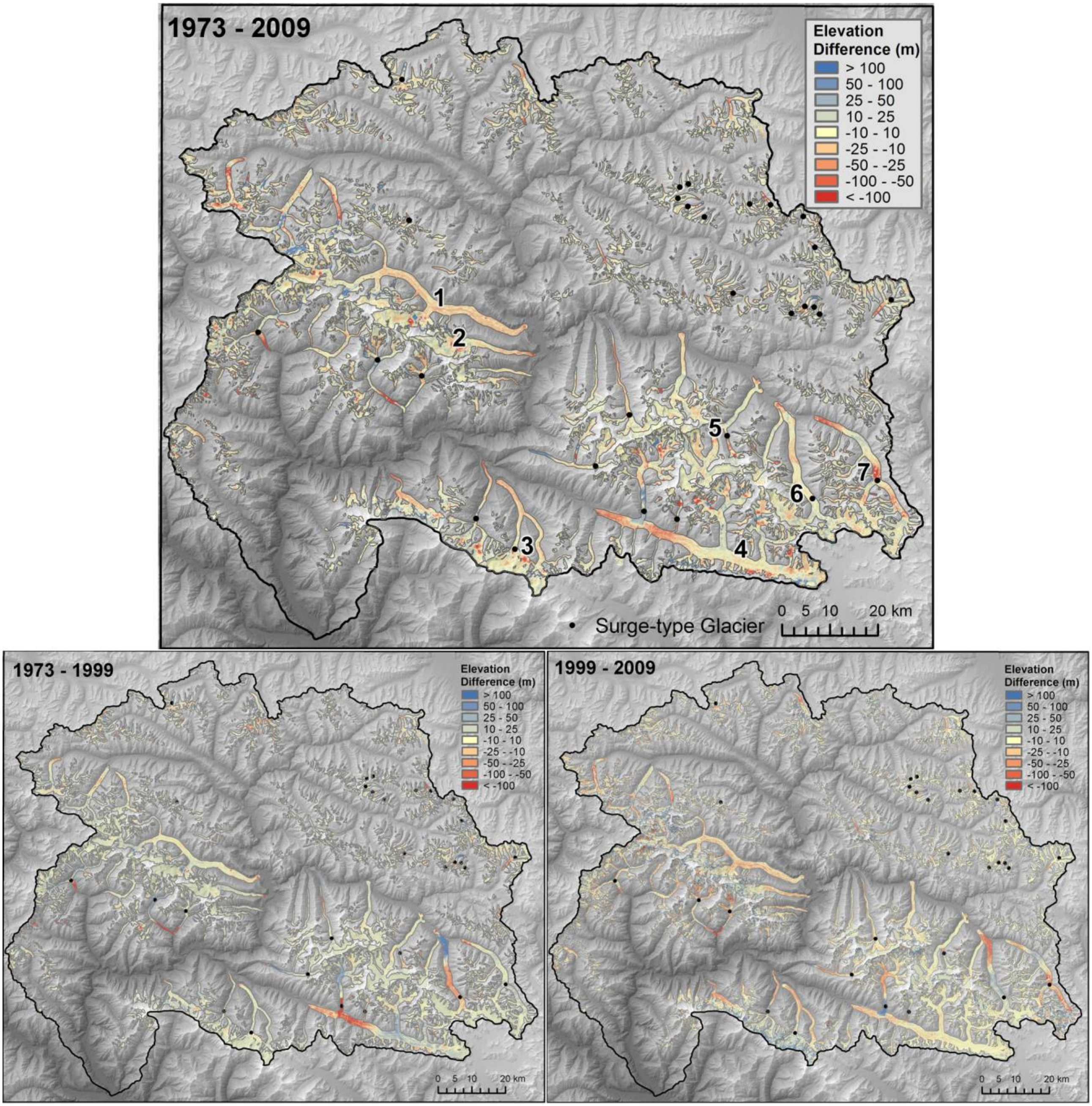

Figure 2: Elevation difference between the ASTER and Hexagon KH9 DTMs (above), the Hexagon KH-9 and the SRTM1 DTMs (below, left) and the SRTM1 and ASTER DTMs (below, right). Black dots indicate surge-type glaciers, the numbers selected larger glaciers: 1: Batura, 2: Pasu, 3: Barpu, 4: Hispar, 5: Yazghil,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

Our extended time series show that glaciers in Hunza Valley experienced no significant mass changes but a heterogeneous behaviour also for the period 1973 to 1999 (Table 1). Hence, central Karakoram glaciers were, on average, in balance for at least the last 40 years. Although longer-term balanced budgets could be assumed 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 confirm for the first time on average balanced-budgets since 1973 using elevation differencing.

Most glaciers experienced similar mass budgets for both investigation periods. However, it seems that some glaciers had more negative budgets post-2000. ~~in the second period than before 2000. T~~This is especially true for the debris-covered Batura Glacier whose tongue showed significant lowering during 1999-2009. S~~Over the entire study period there is also no significant difference in the mass budgets of surge-type and non-surge-type glaciers, a result also found by Gardelle et al. (2013). Also s~~urge-type glaciers~~,~~ also ~~however,~~ showed ~~different surge stages in the two periods and~~ 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). These elevation change characteristics could be due the fact that the active surge event transferred ice mass to lower elevations where it is now more prone to melting. The very high surface lowering of the middle part of the tongue of Hispar Glacier hints also to a past surge event. For the recent period, d~~D~~ifferent tributaries of Hispar Glacier ~~also~~ show clear signs of surging with significant elevation gains ~~surge events~~ (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 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 ~~also~~ 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 m~~M~~ass balance for ~~the~~ different periods and glacier- types

Nr.	Glacier Name	Glacier Type	Area (km²)	Glacier Mass Balance (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~~03~~ ± 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 proven to be valuable for assessing geodetic glacier mass budgets (Pieczonka and Bolch, 2015; Pieczonka et al., 2013, Mauer 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 DTM differences between the utilized DTMs of the off-glacier area shows the in general good agreement but also regions with higher deviations especially for the western part where the quality of the ASTER DEMs w~~h~~ere lower (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 free~~ 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. ~~as a~~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 (a) without void filling (result: mean elevation difference -3.80 m or -0.09 m w.e. a^{-1}), (b) ~~with~~ 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 ~~the~~ average elevation change rates~~values~~ do not change significantly and the deviations are well within the uncertainty. About 10% of the glacierized area in our study region~~s~~ is~~are~~ 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 ~~to detect~~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}.

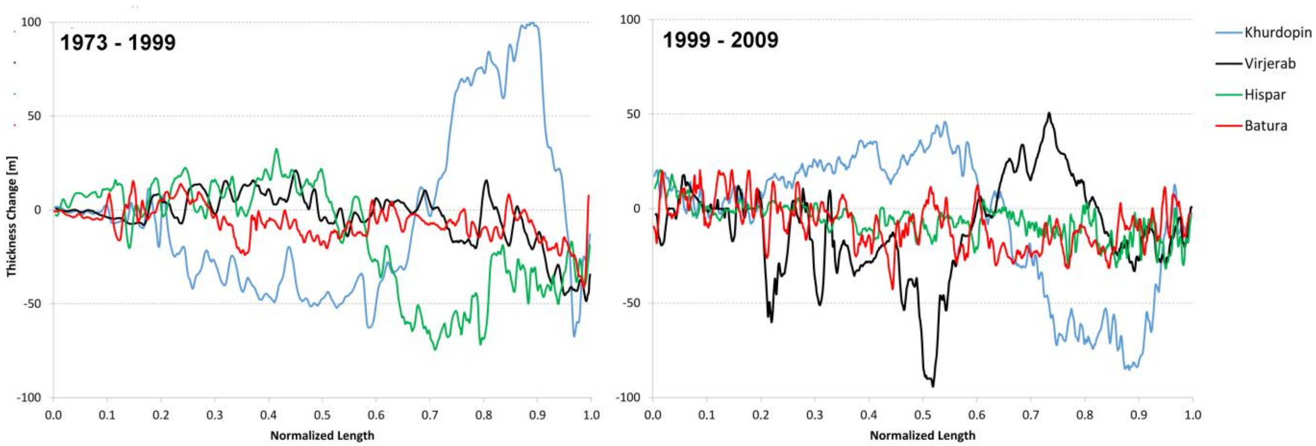

Figure 3: Longitudinal profiles of surface elevation changes for selected glaciers for the two periods.

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. ~~We also~~However, penetration is not an issue for ~~-~~calculation of~~ed~~ the geodetic mass budget ~~for selected larger glaciers~~ ~~for~~over the entire period (~1973-2009) as this uses optical data only. As ~~T~~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 calculations. ~~. The results match well with the results of the two periods and are -0.20 ±0.15 m w.e. a^{-1} for Batura, -0.03 ±0.15 m w.e. a^{-1} for Pasu, +0.05 ±0.19 m w.e. a^{-1} for Yazgil, and -0.08±0.14 m w.e. a^{-1} for Khurdopin Glacier. Hence, even with higher or lower~~

~~radar penetration or different density assumptions, the general statement that the glaciers in the Karakoram experienced on average no significant mass change stays valid.~~

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 based on 1973 Hexagon and ~2009 ASTER DEM data~~for the first time~~ that balanced-budgets in the investigated region are not a recent phenomenon. Since at least the 1970s, glaciers in the Hunza have experienced on average no significant overall mass changes. This is important information as glacier area and length changes represent an indirect and delayed response to climate change and deriving a clear cause and effect relation is difficult to establish. On the other hand, 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. With the 40-year time-period considered here it was possible to show that the overall mass change remains a~~on a~~bout the same but that significant differences exist for individual glaciers~~. exits.~~.

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.

Acknowledgements

This study was performed within the Cryosphere Initiative of the International Center for Integrated Mountain Development (ICIMOD), with the targeted support of the UK Department for International Development (DFID). ICIMOD is funded in part by the governments of Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan, and the Cryosphere Initiative is funded by the Norwegian Ministry of Foreign affairs. The views expressed are those of the authors and do not necessarily reflect their organizations or funding institutions. T. Bolch acknowledges funding through the ESA project Glaciers_cci (4000109873/14/I-NB), ~~and~~ Deutsche Forschungsgemeinschaft (DFG) and The University of Colorado CHARIS project (Contribution to High Asia Runoff from Ice and Snow – (nsidc.org/charis) funded by the United States Agency for International Development~~.~~ We thank F. Paul for his comments on the manuscript.

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