Summary of final author comments

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Title: Four decades of glacier variations at Muztag Ata (Eastern Pamir): a multi-sensor study including Hexagon KH-9 and Pléiades data
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Dear editors,

We thank the two anonymous reviewers for their helpful and valuable set of comments to improve the quality of our paper. We provide below a summary of point-to-point responses to the reviewers' comments and recommendations, as well as changes in the manuscript.

Point-to-Point response to reviews

Review #1

Summary:

Before its publication in TC, however, some structural aspects should be considered. As highlighted in the title, the paper has a tendency to focus a little bit more on technical aspects, which are greats, but thematic insights should remain dominant and be emphasized. The sections Introduction and Study site should be reconsidered. The section Data could be shorten. In the discussion part, the subsection 8.6 does not provide a lot of new informations and could be merged with 5.2.2. The linkage with climate drivers is probably the weaker part, due to the difficulty to have long-term in situ measurements and the lack of previous studies.

Reply: Thank you for your valuable reviewer comments that we addressed below. Our study has also a clear technical focus concerning the employed methods for measuring glacier variations from space, and we tried to bring technical aspects in line with the thematic outcome of our results. Both sections of Introduction and Study site were revised, and the data section was slightly shortened at those parts that you mentioned. We would keep subsection 5.2.2 and 8.6., however, separated and un-shortened, since appropriate corrections for the SRTM C-band penetration are still problematic and cannot be easily addressed, particularly at our remote study site. Inappropriate corrections can have significant impacts on the resulting volume change and geodetic mass balance outcome, and different assumptions need, hence, to be discussed. Please see our individual responses to your specific comments below.

Specific comments

Introduction:

P.1814. Please reconsider the structure of the introduction. The precise description of the Muztag Ata massif (L1-5) should be displaced to the study site. The introduction could open on what we know about the glaciers of the (East) High Mountain of Asia (your review, L10-20), highlighting the difficulties to know something (lack of glaciological data, lack of temporal depth, observed contrasted pattern, "anomalies" respect to temperature changes/other glaciers behavior...). By insisting a little bit more on the relative location of the (East) Pamir massif over Central Asia, the interest of studying the glaciers of Muztag Ata massif could be strengthen (water resources, climate proxy, temperature and precipitation variations...). Same remark for the (great) interest in having a dataset which allows a reconstruction back to 1973. It is also difficult to have an

idea of the relative importance of the Muztag Ata glaciers compared to the East-Pamir or Pamir glacierized area (e.g., you can give a proportion by area).
Reply: We moved L1-L3 to the study site section and restructured the introduction as suggested. L4-L5 was moved to a later part of the introduction. By these changes we also slightly restructured and improved these sentences. The introduction now starts on what we know about the glaciers in (East) High Mountain Asia (L10-L20). By restructuration of the introduction we highlight now more explicitly the specific location of the site. We completely overworked the last third of the introduction according to the suggestions of the reviewer. This concerns in particular a better thematic transition the specific location of the site as well as to the datasets that could be used in this study for a long-term reconstruction.

L 20. Please change paragraph when you address the issue of the climatic drivers.
Reply: Done, new paragraph was inserted.

Study site:
P. 1815. Given the lack of in situ meteorological measurements, you could exploit here the equilibrium-line altitude data to improve the description of the study site. Apparently, this ELA data are not used in the result/discussion sections.
Reply: The equilibrium line altitude data (ELAs) are based on estimates of the first Chinese Glacier Inventory, published in Shi et al. (2008). This data was not collected by ourselves but is based on published results; therefore we did not use it in the results / discussion section. Exploiting the ELA data of Shi et al. (2008) was not part of this study and would go beyond its scope of this already extensive study, consequently we would like to avoid such investigations.

Section 8.4 L9-12 contains useful informations about mean annual precipitation at glacier site which should be cited here. Conversely, L26 to L29 or even to P1816 L7 could be reserved for section 8.4 ("climate change"). In Duan et al, 2007, some analyses performed on the extracted ice core (mentioned here) propose a snow accumulation reconstruction, which could be of some interest for that study (particularly in subsection 8.4).
Reply: Thanks for the hint, we did the suggested changes: We moved L9-12 from P 1834 (Section 8.4) to the end of the study site section. We also moved the other suggested part from P1815 L26 of the study site section to P1834, which is section 8.4 ("8.4 Glacier response to climate change). Thanks for pointing to Duan et al. (2007), we cited this reference and the reconstructed mass balance rates at this point: "*Reconstructed mass balances rates also show much higher wastage after 1990 (-0.42mw.e. a-1), compared to the mean at -0.12mw.e. a-1 for 1960 to 2003 (Duan et al., 2007)*"

Data:
P1816. I guess than this section could be slightly shorten (e.g. P1817. L5-10; L22-26).
Reply: We shortened the recommended data section of the Pléiades and ALOS-PRISM satellites by skipping some less important information and by revising both sections, particularly regarding the ALOS-PRISM sensor.

P1817. Pléiades Data. Please distinguish the accuracy between Pléiades 1A and 1B as mentioned in Berthier et al., 2015 :"Without ground control points (GCPs), the horizontal location accuracy of the images was estimated at 8.5m (CE90, Circular Error at a confidence level of 90 %) for Pléiades-1A and 4.5m for Pléiades-1B (Lebègue et al.,2013)."
Reply: We now distinguish the accuracy between Pléiades 1A and 1B as suggested. The results of Lebègue et al. (2013) are also mentioned by Berthier et al. (2014).

P1817 Line 15: this sentence is unclear to me. What zone does the image of 3 August 2013 cover ?
Reply: This image of 3 August 2013 only covers some cloud-covered areas in the image of 19 June 2013 in the south-west. We made this clearer in the manuscript.

Data processing:
P1820. Could you precise the proportion of GCPs extracted from ICESat, and SRTM respectively, and the number of checkpoints for each source.
Reply: Measuring Check Points was initially not foreseen since it was already difficult to find suitable Ground Control Points in this remote and mountainous region. In case of Hexagon KH-9 we decided to use two initially as Ground Control Points measured coordinates as Check Points due to high residual offsets in bundle block adjustment. These Check Points might eventually not have been measured correctly enough (which explains the high residual offsets) and were not investigated further. We therefore decided to omit this information in the manuscript and eliminated the paragraph *"…but two of them showed high residual offsets and were subsequently set as check points*" (page 1820, line 15 to 16). We modified the sentence of the SRTM / ICESat proportion (line 10 to 11) as follows: "*The SRTM-3 DEM served as z-reference for one third of the GCPs, since no ICESat information was available*".

P1822.L4 Which software or programming environment did you use to perform the analytical approach ?
Reply: We could take advantage of a program in Python programming language that was written by Tino Pieczonka (see acknowledgements). This program was successfully used for co-registration in Pieczonka et al. (2013). We make this now (more) explicitly clear in the manuscript.

Assessment of glacier variations:

p1823. L14. How many glaciers do represent "all glaciers" ? If you generated the inventories from the Pléiades data first (2013), I therefore suppose you that you did not notice any complete glaciers disappearance since 1973 ? Have you in mind to propose this inventory to the WGS, GLIMS or RGI databases ?

Reply: The word "*All*" (line 14) might be irritating and we deleted it. We did, by now, not investigate the number of glaciers at Muztag Ata and their disappearance. The definition of our study site to the East was depending on the coverage of our remote sensing datasets, and several additional glaciers to the East could therefore not been taken into account that eventually still might belong to Muztag Ata. We also think that area changes are more meaningful than an absolute number of mapped glaciers. To this regard, results might wrongly interpreted in case that a retreating glacier would split in two parts, resulting in an increase of the glacier count. Meanwhile the Chinese Glacier Inventory is published which includes this region. However, we will use our data for comparison with the other existing inventories as T. Bolch is actively involved in the activities in the international bodies. The results will also be reported to WGMS.

P1824. The sentences from L5 "All three [...]" to L11 should be move to subsection 4.2.2. You selected thirteen glaciers according to their orientation and size. Which is the representativity compared to the elevation range ? I guess that an extra figure showing area vs. hypsometry of the all glacierized area could help. Which proportion is windward or leeward, according to the north-south "natural" separation ?

Reply: We moved the sentence from line 6 to line 8, as suggested, to subsection "*4.2.2 DEM extraction*". The previous sentence from line 5 to line 6 was moved to section "*4.3.2 DEM co-registration*" since it is related to a processing step after co-registration. The sentence from line 8 to line 12 fits, in our opinion, best to this section, since it describes the problems of SRTM voids for geodetic glacier mass balance calculation and how we handled it. In section "*2 Study area*" we describe that the Muztag Ata Massif is divided "*into a windward area with small valley glaciers exposed towards the westerlies and an eastern leeward part with higher gradients*" (page 1815, line 14 to 15). Since windward is exposed towards the westerlies, the proportion can be derived from the glacier orientation in e.g. Figure 1. The investigated glaciers are all situated at the same mountain massif (Muztag Ata), and the ELA in Table 3 can give a first impression regarding the elevation range. We agree that an extra figure showing area vs. hypsometry is helpful, therefore we do now provide such a figure as part of this article by adding the information "*The maximal extent of glaciation was observed to be at ~5000m (Fig. 3).*"iIn chapter "7.1 Glacier area and length changes".

P1824. L20 You could also have consider the mean of the glacier sizes for the two dates (Zemp et al., 2013).

Reply: This might have been one possibility, but we decided to use the maximal extend of the glacier sizes for the two dates by following many other comparable studies such as e.g. Neckel et al. (2013) who employed the geometric union of both glacier extends.

Neckel, N.; Braun, A.; Kropáček, J. & Hochschild, V.: Recent mass balance of the Purogangri Ice Cap, central Tibetan Plateau, by means of differential X-band SAR interferometry, The Cryosphere, 7, 1623-1633, 2013.

P1825 L24 By ice, do you mean "summer surface" (see Cogley et al.,2011) ?

Reply: Yes, we meant in this context "summer surface", and replaced the word "ice" with "surface" *("… at the end of the melt season in 1999*")

P1826 L2 Could you check the sign of the offsets ? I am probably wrong on that, but I would have say the contrary

Reply: The offsets should be correct as presented, and result from the DEM differencing approach: "*Geodetic glacier mass-balances are based … differencing elevations of older dates … from more recent elevations* " (page 1824, line 1 to 3). The offset is positive if SRTM is representing glacier surfaces of older date (1999-2009/2013) because the "older" SRTM surface needs to be corrected for penetration. In case that SRTM is of newer date, the sign of the offset needs to be inversed, since the older dataset (here KH-9 Hexagon) is subtracted from SRTM.

Discussion:

P1831 L1 to 4: the end of the sentence is unclear to me. Why do you expect less glacier shrinkage at Muztag Ata ?

Reply: We changed the word "subject to" with "by reason of", and changed the sentence as follows to explain we would expect less glacier shrinkage: "In total, we would also expect less glacier shrinkage and retreat at Muztag Ata as in other areas of the Eastern Pamir study region of Yao et al. (2012) by reason of, on average, nearly balanced observed mass budgets in this study."

P1830. Surges are not linked with mass gain. Surges complicate the interpretation of glacier variations, but in my opinion it should not be directly "opposed" to the glacier shrinkage. Such ambiguously formulation is also present in the introduction (P1814 L15: "but"). Apparently, you did not observe surges in your glacier indicators variations ? If it is true, you could mention it.

Reply: We fully agree with the reviewer, that surges are not linked to mass gain and complicate the interpretation. The mass is redistributed from the accumulation area with elevation gain in the lower part but loss in the upper part of the glacier. However, a surge typically leads to a rapid advance followed by shrinkage. We observed that glaciers fluctuated or even advanced during the study time period at Muztag Ata. Regarding our data, we assume that Kuokuosele Glacier and possibly Kuosikulake and G075075E38189N Glacier might be in a surging process. (see also P1828 L25ff, section "7.1 Glacier area and length changes"). We reformulated the sentence *"This seems to be contrary to the observed high shrinkage in the Zulumart Ranges south of Pamir Alay…*" (P1830 L15ff) to "Contrary *to this trend was high shrinkage observed…*" for clarification. We moreover changed the ambiguously formulation in the introduction in the sentence on P1814 L15 to *"…average, while several glacier surges were observed at the same time*".

P1831: it should be interesting to say something about mass-balance variations along a vertical profile.
Reply: Are you addressing a specific glacier? We for example already show the vertical profile of elevation changes for Kekesayi Glacier as part of Figure 3 (*"…The profile shows the surface velocities and the corresponding down-wasting (1973–2013) along the central glacier flow line…"*). By having in mind the already numerous figures of this publication, we would not provide an additional Figure with further vertical profiles of other glaciers.

P1832 L3 to 11: this sounds very interesting. Being very careful, do you think we can make any assumptions about common (topo-)climatic (or meteorological, given the short period) drivers ("strengthening werterlies" ?) to make a link with section 8.4? Maybe some regional meteorological datasets could help (CRU/GPCP), and some references: a short review on that question (in French): (Berthier, 2015), about Global Precipitation Climatology Project (GPCP): (Adler et al., 2003), about the seasonality of the observed precipitation trends: (Fujita, 2008; Kapnick et al., 2014), and eventually about the elevation influence: (Hewitt, 2011).
Reply: By being very careful with this statement, we suppose that there is a positive anomaly when comparing our findings with the results of these cited publications. Such an anomaly was already postulated by Yao et al. (2012), as mentioned in chapter 8.4 (P1834, L17ff). Your approach sound very interesting, but we think that any further assumptions beyond our careful statement would go beyond the scope of this study. Such assumptions would be rather speculative without further investigation and profound analysis, that would, for sure, be truly interesting.

P1832 : maybe you can cite Zhou et al., 2013 to complete the comparison on glacier surface dynamics ?
Reply: Thank you for the hint, we now consider Zhou et. al (2013) for surface dynamics comparison. To this regard, we added to the sentence "*The average upstream velocity of up to 50m per year (~14 cm per day) is in the range of our measurements*" (P1833, L14-15) the following subordinate clause: *"…, while Zhou et al. (2014) presents winter velocities that did not exceed ~11m per year from 2008 to 2010*".
Zhou et al. (2014) and Yan et al. (2013a) used ALOS PALSAR data of the similar dates (14/01/2009 – 01/03/2009 i.e. 46 days) to estimate the velocity. They used the similar technique (Normalized Cross-Correlation Technique) for velocity estimation, however Zhou et al. (2014) upscaled velocity is not more than 11 m/year whereas Yan et al. (2013a) estimated the maximum average velocity of 34 m/year. Yan et al. (2013a) provided the summer and winter velocity of 2009 using ALOS PALSAR. We have used the similar months during the summer of 2011 but with TerraSAR-X data. Despite the different dataset and year, our results are comparable with Yan et al. (2013a) that make much more sense to us, and this is why we would not discuss Zhou et al. (2014) more in detail. The publication of Zhou et al. (2013), however, provides some interesting information about the study site, so we also considered some information of this reference in the introduction and the study site section.

P1833 L27 to P1834 L3: due to the very different time periods considered, I think that it is out of the scope of this study. You can move it to the introduction section or simply remove it.
Reply: The studies of Seong et al. (2009a, b) are one of the few detailed investigations that have been employed at Muztag Ata, and we would therefore like to keep it in the manuscript. However, as also remarked by the second reviewer, we moved this paragraph to the revised introduction, and also shortened it.

P1834 L20: Is it possible to better characterize this "cooling period" in temperature and precipitation changes ?
Reply: We cited this information from Shangguan et al. (2006), who unfortunately do not provide further data, expect of an additional climate diagram from Taxkorgan meteorological station. We could not find further information to better characterize these "cooling periods", and had to rely on the following information of Shangguan et al. (2006): "*This time-span included three cold periods: 1961–68, 1973–77 and 1985–93*.", and "*However, some glacier advances might be a response to the three periods of cooling and the increase of annual precipitation…*"

Conclusion:
The conclusion should tell something about the possibility of a wide-regional "positive anomaly" (from section 8.2 and 8.4).
Reply: This is true, and we changed the sentence "*Slightly positive observed budgets after 1999 are, however, more likely a response to strengthening westerlies with increasing snow accumulation*" as follows: "*Slightly positive observed budgets after 1999, however, could possibly reflect a regional-wide positive anomaly with increasing snow accumulation from strengthening westerlies*. "

Table 1: please precise which images are from Pléiades 1A or 1B.
Reply: We now precise in Table 1 which images are from Pléiades 1A and 1B

Table 4: you should consider a more classical chronological way: 1973-1999; 1973-2009 and so on.
Reply: We revised this table in a more classical chronological way, as also suggested by the second reviewer. The order is now 1973–2013, 1973–2009, 1973–1999, 1999–2013, 1999–2009, and then 2009–2013. By organizing the periods in this order, we can first present the total periods of 1973–2013 (and 1973–2009) in the first two columns, and then the sub-periods as it is suggested by the second reviewer, by still keeping a chronological order in this way. The last column contains

the very short sub-period 2009–2013 that should be considered, as mentioned in the manuscript, as too short for reliable results.

Figure 1: this figure is a little bit dense. Glacier extents variations are difficult to read (particularly 2009 outlines, in blue). You should propose a new figure, highlighting the location of Muztag Massif in a "regional" context (with Taxkorgan meteorological station location and hydrological network for example). Extracted ice core location could be also mentioned.
Reply: We modified this figure accordingly with several changes and improvements according to these suggestions. By enlarging the scale from 1:400.000 to 1:250.000 (when printed out) we now provide a better overview of the Muztag Ata massif, and glacier extend variations are easier to read. To this regard we also changed the color of the 2009 outlines from blue to red. Taxkorgan meteorological station as well as the ice core location (cf. Tian et al., 2006; Duan et al., 2007) is now also mentioned in this figure. We also made the background satellite image brighter for better readability of the glacier outlines. The overview map at the lower right was also modified. It is now smaller and by also enlarging its scale it sets Mutzag Ata to a more regional context.

Figure 2 is constituted by two type of images: please split it into two figures or choose between one type of data. Distortion vectors image (KH-9) is maybe less common.
Reply: We agree and have split Figure 2 in two separate figures, resulting in one additional figure. Both (sub-) figures show important information, on the one side the high quality of the 1m-resolution Pléiades DTM (with the clearly visible steep and advancing glacier tongue of Kuokuosele Glacier), on the other side the effects of film distortions. In this context are the distortion vectors that visualize the film distortion from unprocessed KH-9 imagery of particular importance, as mentioned in chapter "4.1 KH-9 image pre-processing"

Figure 3: maybe the title should be remove; Muztag Ata is also a glacier, so it is a lit bit confusing.
Reply: *We agree and removed the title from the figure (new figure).*

Figure 4 to 6: you should consider a more classical chronological way, starting from 1973 (see also table 4).
Reply: *We tried to order the figures in a more classical chronological way by following the modified order of Table 4 (see previous comment). Figure 4 as the first figure of difference images presents now both total periods of 1973–2013 and 1973–2009, accordingly to Table 4. Figure 5 presents the periods 1973–1999 and 2009–2013, and Figure 6 the periods 1999–2013 and 1999–2009. Presenting in two sub-figures the difference images of 1973–2013 vs. 1973–2009 in Figure 4 as well as of 1999–2013 vs. 1999–2009 in Figure 6 allows to easily comparing both periods with similar timeframes. This is not the case in Figure 5, and if desired we can split its both sub-figures into two separate figures, or to switch the order with Figure 6.*
As a result of the new order, we changed the order and renamed the data files of Figure 5 to Figure 4, Figure 4 to Figure 6, and Figure 6 to Figure 5. Figure 5 was newly created since we switched to position of both sub-figures to follow the new chronological order.

Technical corrections

P1813 Line 10: you should precise the year (2011) for the TerraSAR-X amplitude tracking.
Reply: The year 2011 was added, as suggested.

P1813 Line 11: you should precise: "[...] temporal glacier variations [...]".
Reply: The word "*glacier*" was added at this position, as suggested.

P1815 Line 18: when introducing Kekeyasi Glacier for first time, please precise that the number into parenthesis is a GLIMS Id. The word "Glacier" is missing after Kekeyasi.
Reply: We precise that the number into parenthesis is a GLIMS ID at the beginning of chapter "7 Results", page 1828 line 2 to 3. Before that, the GLIMS ID is only mentioned twice and in the context of well known Kekesayi Glacier. Since this is the only specific glacier that is mentioned before, we therefore eliminated the GLIMS ID from Kekesayi Glacier at page 1815, line 18 (and added the missing word "Glacier") as well as page 1826 line 7.

P1816 Line 13: please precise that the number into parenthesis refer to the mission Id.
Reply: We added the word "mission numbers:" into the first parenthesis and moved them to the end of the sentence.

P1818 Line 5 : it is maybe clearer if you give the date information first : "The data was acquired on 10 September 2009, and provided with RPC".
Reply: We changed the sentence as suggested (without comma).

P1827 Line 12: is the verb "be" correctly located ?
Reply: We do not see a verb "be" at this position… do you mean at another line? (Sentence in this line: *"…multi-temporal DEMs (cf. Höhle and Höhle, 2009). Similar to DEM co-registration, is …"*)

P1832 Line 3: please change paragraph.
Reply: OK, paragraph changed.

P1836 Line 23:"eventually"should be replace by "possible" or an equivalent adjective (this confusion seems to appear in some other parts of the text).
Reply: We would not change "eventually" to "possibly" since we believe that our penetration depth correction is correct. However, there might be some underestimation, but this is rather "potentially" as "possibly" the case. Hence, we used the word "potentially", and also replaced "eventually" at page 1820 line 22 with "potentially" and at page 1836 line 2 with "possibly".

P1837 Line 13 to 15: is the verb "present" correctly located ?
Reply: We changed the order of the words to correct for the location of the verb "present": "*This study presents, in combination with the recently recorded high-resolution Pléiades imagery, the longest time series…*"

Review #2

Summary:

Generally, following changes could help to improve the presentation of data, methods and results as well as the discussion: The climate data is now part of chapter 2, Study area. This should be part of the data section, and the location of the climate measurements should be evident from Figure 1. At least seasonal mean(s) winter precipitation, summer temperatures) should be shown in a graph, as these are discussed later. Where in the introduction only one station is located above 3000m, later on high elevation climate changes are discussed. It would help to have more clarity on the data base. The methods, results and discussion parts are mixed up somehow. The term mass balance is used for geodetic mass balances as well as direct mass balances in the same paragraphs, which is confusing. If mean annual change rates are derived from geodetic balances, it should be clearly distinguished in the phrasing from measured annual balances, as the difference could be high. The presentation of the periods is also confusing, I would recommend to present the total period 1973-2013 and the subperiods (1973-1999, 1999-2009, 2009-2013). I miss a general discussion if the accuracy of the DEMs does allow this high temporal resolution, when large parts of the glaciers show low altitude changes. The amount of snow covered or oversaturated area should be indicated in the remote sensing images, which would be nice to see in the article. The impact of the method for calculating dh on the volume change and mass balance should be more explicitly discussed. Some of the following detailed comments might just be a hint on a lack of clarity in the description, but should help to find out where changes in the text could help to avoid such misunderstandings.

Reply: Thank you for your comments, and please have a look to our detailed individual responses below. Our study does focus on the investigation of glacier variations at Muztag Ata from space, and an essential part of our research concerns the derived (geodetic) mass balance results. We did not intend to provide a detailed background of the local climate and think that such additional investigations would go beyond the scope of this already extensive study. By addressing this point, we did not employ any climate measurements at Muztag Ata as part of our study, all climate data mentioned in this manuscript was cited from already published results. We tried to make this now clearer at several points in the manuscript. Maybe there has been some misunderstanding by the reviewer, which is reflected in some parts of our author responses. In our understanding we clearly separated methods, results and discussion chapters. We agree that it should be clearly separated in between geodetic and in-situ derived mass balances, and we tried to make this clearer according to your specific comments. We also agree that the presentation of the periods in Table 4 was confusing and we changed now the order .A temporal resolution of ten years or more is generally considered as long enough for geodetic mass balance assumptions as it is the case in this study, and the problem of the short time period of only four years from Pléiades to ALOS-PRISM is clearly addressed in our manuscript (P1829 L24ff). Low altitude changes give in this context no conclusion regarding the accuracy of the DEMs and the outcome. We employed extensive uncertainty estimation, and in case that the uncertainties are higher as the observed glacier variations, this would just indicate that the variations are not significant. Please see our individual responses to your specific comments below, and thank you again for reviewing our manuscript.

Specific comments

Abstract: 1:
Does this first sentence refer to results of this study, or to direct measurements? Is there a research question to ask here to explain the aim of the study, e.g. to find if these measurements represent singularities or largescale mass balance trends?
Reply: The first sentence refers to recent results of previous studies. To make this clearer we replaced "*recent*" by "*previous*" in this sentence. To point out our research question and motivation more clearly, we added "*contrary to the*

global trend", to demonstrate that the previously observed results are contradictious to what is observed elsewhere. We focus on singularities and largescale trends later in the abstract.

12: What is meant by fluctuated or advanced? Aren't fluctuations advances and retreats?
Reply: True. We observed that some glaciers show only an advance on the available images , but some fluctuated, thus showed an advance and retreated during the period of the study, or vice versa.

13: Did you really observe continuous shrinkage, or just in the resolution of your data (maybe missing some short annual or seasonal advance?)
Reply: Continuous shrinkage to this regard means that we observed significant (in terms of uncertainty calculation) and subsequent glacier shrinkage in all of the employed remote sensing data. We can, however, not preclude that intermediate short annual or seasonal advance occurred.

14: What is a visual advance, do you mean that as synonym of meaasureable, or as contrast to any other (radar?) method?
Reply: This means that no change was obvious in the imagery by visual investigation, and to this regard it means "measurable". We changed "visible" by "measurable" to make this clearer.

21: The choice of presenting overlapping periods is somehow obscure. If the accuracy of the DEMs and the amount of seasonal snow does allow a presentation of the single periods, I would prefer that. If not maybe just present 1999-2013?
Reply: The fact of having overlapping periods results from the scarce availability of stereo satellite imagery in the remote region. A part that only very few stereo satellite imageries are available that cover the site, several of them are covered too much by clouds and / or snow, or are not useful due to other limitations (e.g. acquisition season). We oppose the statement that overlapping periods would be obscure, we rather think that this approach proves the quality of the derived results. By having overlapping periods we could show that our results, derived from different sensors, are in line with each other.

1814 16-20: For which periods have these mass balances been measured?
Reply: From line 12 to 14 we mention that the subsequent studies (as Gardelle et al. (2013) from line 16 to 20) refer to the "*last decade*". We added "Since 1999" to the study of Gardelle et al. (2013) due to varying time periods from 1999 to 2008/2010/2011, depending on the study site. We now mention "*from 2003 to 2008/09"* for the study of Gardner et al. (2013) from 2003-2009 and Kääb et al. (2015) from 2003 to 2008.

23: Is this really gridded data, and what is the variability? Or do these numbers refer to a specific station (in this case we would like to know which station, coordinate, altitude : : :). What is the reference period of the presented anomaly? Are the 7.4 mm /decade significant? Please also give the annual mean and precipitation of the reference period.
Reply: The presented data is not part of this study, but was already published before by Zhang et al. (2012). We already cited this publication in the subsequent sentence, but moved the citation now directly to the referenced data to make things more clear: *"…+0.3 °C and +7.4mm (Zhang et al., 2012)*." We think it is beyond the scope of this manuscript to further analyze the presented climate values in the publication of Zhang et al. (2012).

24 ff: What do you mean by warming? A seasonal mean would be better than a annual mean. How many stations and where, in which elevations, show changes in which climate parameter? Does that mean that close to these glacier tongues stations are located? Maybe shift this paragraph to the data section and describe the measurements more extensively.
Reply: Similar as in case of the previous comment, this was cited from previous results. Climate data was cited from Zhang et al. (2012) (see previous author comment), the subsequent statement from Yao et al. (2012). We, again, think it would be beyond the scope of our foreseen publication to analyze the results of Yao et al. (2012) more in detail, since this study should be focused on glacier variations at Muztag Ata and not on climate variations. We did not collect any climate data as part of this study. All data used in this study is already presented in the data section.

1815 20: Here comes another piece of climate, please shift that to the data section. Why do you present annual values and not seasonal ones? 27: Is summer June July August or May to September? I do not get the message: Did you compare periods (which) or calculate a trend (how) to end up with a warming of 0.7C. Is 1957 the start of your period and 2000 the end? But what did you compare that to? Please explain that more explicitly preferable in the data section.
Reply: Climate data mentioned at P1815 L20ff is cited from other publications. We think that we clearly and properly cited references from the already published climate data. Since it is not our data, it makes, hence, to our understanding no sense to move such information to the data section and to explain it more explicitly. Please also note that reliable climate data at our remote study site is really rare, and we therefore have to rely on the sparsely published data that is available to the scientific community. Our study is based on remote sensing data from space. We did, hence, NOT compare or calculate any trends related to such or previously mentioned climate data, but we have cited the information that was available, here from Taxkorgan meteorological station that started operation in 1957 (cf. Shangguan et al., 2006). Unfortunately, we could not find published seasonal values, and we think that this would go beyond the scope of shortly presenting the study site. We could, though, find information that the mean summer temperature from 1957 to 2010 at Taxkorgan was measured at 15.1°C (cf. Yan et al., 2013b; Yang et al., 2013). This information was added to the manuscript. Summer temperature means here from June to August (cf. Shangguan et al., 2006), this information was also added to the manuscript. Please also remark that we moved L9-12 from P 1834 (Section 8.4) to the end of the study site section, and that we moved the part from P1815 L26 to P1816 L7 of the study site section to P1834 (section 8.4), as suggested by the other reviewer.

1816 3: is there a reference to cite, at least any indication where this information comes from?

Reply: The reference was cited in the subsequent sentence. We now also mentioned the similar reference at this sentence to make things clearer. Please note that we moved the section from P1815 L26 to P1816 L7 to P1834 (section 8.4), as suggested by the other reviewer.

5: Where was a warming observed – in the core? Or was it an isotope variation, which is for sure not related to a shift in the precipitation regime? What means the 'from2,0 C to 2.4 C – a range for different stations, an error bar, different periods, an altitudinal effect? Does it make sense to compare a station at 3000 m with a station (or whatever) at 7000 m? And why?

Reply: Similar as for the previous climatological measures at Taxkorgan, this is not our data, and we cited here results from the study of Tian et al. (2006). The ice core at 7000m a.s.l. was drilled by Tian et al. (2006), and the data at 7010m a.s.l. was coming from this ice core. "*The detailed annual δ18O in ice core record allowed us to compare it with the local meteorological station air temperature data. The annual variation of δ 18O in this ice core is consistent with the local air temperature record from the Taxkorgen meteorological station."* Tian et al. (2006). The comparison with the Taxkorgan station data as employed by Tian et al. (2006) makes sense since the VARIATIONS of temperature are in good agreement. "*From2,0 C to 2.4 C*" means that a "*warming trend of +2.0 to +2.4°C per decade*" was observed by analyzing the ice core: "*The regression result shows that the decadal warming trend is around 2.0~2.4°C per decade from the decadally averaged temperature at Muztagata, while only 0.18°C per decade for Taxkorgan meteorological station*" (Tian et al., 2006). We believe that we adequately presented the relevant results of Tian et al. (2006) in the manuscript which allows extracting the necessary information properly. Please note that we moved the section from P1815 L26 to P1816 L7 to P1834 (section 8.4), as suggested by the other reviewer.

1818 12: Are the images free of seasonal snow?

Reply: We did not mention explicitly that imagery was acquired under the premise of having a minimum of cloud and snow cover. This is not only important for the Landsat dataset as commented here, but particularly for the DEM extraction process of stereo imagery which were acquired in summer (see Table 1). The employed Landsat dataset of 11 September 2000 is shown in Figure 1. It can be seen that the Muztag Ata study site is virtually free of seasonal snow in this image, but that the mountain range east of the site is locally affected by some snow coverage. This was the best image of all available Landsat datasets for about the year 2000 in terms of cloud and snow cover. We now inserted the following sentence at P1816 L9: "Imagery was acquired under the premise of having a minimum cloud and snow cover"

15ff: What about the steep parts – was the geometry of SRTM sufficient to map all the areas? Which parts were hole filled?

Reply: The geometry was sufficient as reference for co-registration of all extracted DEMs as well as for mass-balance calculations. For high resolution mapping purposes we could take advantage of our extracted Pléiades DEM at 1m resolution (see section "5.1 Glacier area and length changes"). We excluded steep parts in our data processing, as mentioned on page 1822 L22-L24: "*The vertical accuracy of SRTM-3 decreases in case of steep terrain, and we thus only considered flat areas until a slope angle of 10° (Falorni et al., 2005)*". Hole-filled parts could be identified by a mask provided by the Consultative Group for International Agricultural Research (CGIAR) (see page 1818, L19-L21). "*SRTM voids are particularly observed at steep slopes and mountain ridges, while most of the glacier areas consist of non-interpolated data. We restricted mass-balance calculations to the original SRTM-3 surfaces and excluded gap-filled voids because of high inaccuracies* " (see page 1824, L8-11).

1819:1: What about the snow conditions then?

Reply: We are not sure if this comment is related to page 1819 L1 as indicated (section "3.6 TerraSAR-X": "…10 August and 1 September 2011 during the descending pass of the satellite."). Since imagery was recorded in summer, low seasonal snow can be expected in the ablation area. Good results were also achieved in some parts of the accumulation area, as can be seen in Figure 3. Information about that was added in the manuscript: We reformulated the sentence "*To determine surface velocities of Kekesayi Glacier we employed amplitude tracking*" (P1826, L7-8) to "*Surface velocities of Kekesayi Glacier were determined by amplitude tracking that also performed well in most parts of the upper glacier area*". Phase-based methods such as DInSAR failed due to low coherence (page 1826, line 12), therefore we had to use amplitude tracking with known limitations in low contrast areas. If this comment is related to snow conditions in the SRTM dataset, please refer to section "5.2.2 SRTM-3 C-band radar penetration" and "8.6 SRTM C-band penetration depth correction" where we explain how we took snow conditions into account.

6: I did not really get if you excluded the moving ice and snow areas for coregistration. Did you?

Reply: Page 1819 Line 6 is pointing to the title of section "4 Data processing". We therefore assume that the comment is referring to "4.3.2 DEM co-registration" on page 1822 line 3. To this regard, we mentioned on line 4 to 6 that "for each DEM we calculated its difference image relative to SRTM-3 by excluding non-stable terrain such as (rock) glaciers, ice-cored moraines and lakes.". All non-stable (and moving) areas were, hence, excluded for co-registration that is based on this difference image. We might be wrong, but we cannot actually see a relationship of this comment to subsequent section "4.1 KH-9 image pre-processing" on line 7ff.

1820: 10 What about the ICE SAT footprint – which accuracy has the elevation of this data in the view of the rough terrain?

Reply: GCPs were only situated at stable and plain terrain, in general at a slope at less than 10°. Since this is was by now not clearly explained, we changed the sentence on page 1820 line 7 to 9 as follows: "*GCPs were situated at stable and plain terrain, ideally close to laser altimetry measurements of the Ice Cloud and Elevation Satellite (ICESat)…*". Accuracy of elevation datasets such as ICEsat and SRTM decrease with steeper terrain. In case of SRTM this was mentioned (in another context) on page 1822 Line 22 to 24: "*The vertical accuracy of SRTM-3 decreases in case of steep terrain, and we thus only considered flat areas until a slope angle of 10° (Falorni et al., 2005).*". ICEsat provides a much higher vertical accuracy as SRTM, and elevation inaccuracies at GCP positions can therefore be considered as marginal for ICESat as compared to SRTM. In case of SRTM is the accuracy *"stated to be ±6m relative and ±16m absolute (Rabus et al., 2003)."* (Page 1835 line 4 to 5). An ICESat-spot is 65-70m in diameter at 175m separating distance of each spot, with a horizontal accuracy of 10.6±4.5m of spot geo-location, and a vertical accuracy of up to ±34cm (±6.7 cm under best conditions) according to Magruder et al. (2007). Kääb et al (2012) successfully used ICESat in rough terrain for glacier thickness and mass change estimates over the Hindu Kush–Karakoram–Himalaya region. We did not provide accuracy information of ICESat in the manuscript due to the high accuracy of ICESat compared to SRTM, which has a much higher impact to the error budget as ICESat.

Magruder, L. A.; Webb, C. E.; Urban, T. J.; Silverberg, E. C. & Schutz, B. E.: ICESat altimetry data product verification at White Sands Space Harbor, IEEE Transactions on Geoscience and Remote Sensing, 45, 147-155, 2007.

1821 25: Would be nice to indicate erroneous parts in the map and find them in the discussion of the uncertainty of the geodetic mass balance.

Reply: Erroneous parts were excluded from the DEMs and are subsequently not affecting the elevation difference images to DEMs of other dates. Erroneous elevation values at poor quality are, hence, not affecting the geodetic mass balance and its uncertainty directly, since they were set no-data in the DEMs and, thus, in the difference images . Regarding (resulting) gap-filling and also further outlier processing for geodetic mass balance calculation, please refer to section "5.2.1 Outlier detection and gap-filling" on page 1824. By considering also the noise of poor quality elevation areas, and for clarity reasons, we would not recommend to map such parts in the difference images.

1822: 3: Did you exlude moving parts (glaciers) from coregistration?

Reply: We think that this comment is referring to the previous author comment "*1819 6: I did not really get if you excluded the moving ice and snow areas for coregistration. Did you?"* Yes, moving (glacier) parts were excluded for coregistration, based on the calculated difference images: "*For each DEM we calculated its difference image relative to SRTM-3 by excluding non-stable terrain such as (rock) glaciers, ice-cored moraines and lakes*." (page 1822 line 6 to 8).

1823: any decorrelation ?

Reply: This is probably refereeing to section "4.4 SAR image co-registration". We are not sure if we correctly understood the comment. We employed amplitude tracking instead of phase based methods, since "*it was not possible to retain the interferometric phase due to temporal decorrelation*" (page 1826 line 9). The imprecise matching of the glacier surface features was estimated over non-moving terrain, as mentioned in section "*6 Uncertainties of glacier variations*". A SNR (signal-to-noise ratio) of 4.0 is used to select the correlated windows which are 94 % of the windows in our dataset, undergone the amplitude correlation. The offsets determined for these correlated windows are further employed to estimate the bilinear offset polynomial. Hence the amount of decorrelation is less than 6 %

11: I would see here rather a section on results with subchapters: : :

Reply: The previous chapter "*4 Data processing*" presents necessary pre-processing as well as more general data processing steps that were needed for later glacier assessment (chapter 5). This chapter now presents in three sections our approach how we assessed glacier variations with our data: "*5.1 Glacier area and length changes*", "*5.2 Glacier mass-balance*" and "*5.3 Glacier surface velocities*". Following chapter 7, after explaining the uncertainties of glacier variations, is then presenting the results.

1824: 1: So this is rather a chapter on geodetic balances, which I would like to read in the title. What about seasonal snow, the accuracy of the DEMs and the resulting maximum temporal resolution? This could be stated in a section on methods, together with the density assumption. As the geodetic balance can only be calculated for the full glacier area, especially in case of surging glacier, how did you proceed with data gaps? What was the threshold for example to skip a glacier in case a part of the area was not mapped? Why did you choose these glaciers?

Reply: We changed this title and the title of chapter 7.2 to "*Geodetic glacier mass-balance*". This is still a section on methods, as we present the steps that we employed to assess glacier variations based on our data. We hereby assume an ice density of 850±60 $kg\ m^{-3}$ (Huss, 2013) (page 1824, line 18). We calculated the geodetic balance on the full glacier area. Gap "*…filling of remaining δh voids in glacier areas were employed separately for each glacier accumulation and ablation zone*"(page 1824, line 24-25). Our approach to proceed with data gaps are explained in subsequent section "*5.2.1 Outlier detection and gap-filling*". Particularly regarding glaciers of different size due to temporal changes (also regarding surging glaciers), was their size "*defined by the largest extent of the correspondent mass-balance investigation period*" (page 1824, line 20 to 21). The accuracy of the DEMs is estimated by the Normalized Median Absolute Deviation (NMAD), summarized in Table 2 and described in chapter "*6 Uncertainties of glacier variations*" (page 1827 line 10). The satellite images were acquired in summer and were virtually free of seasonal snow (see also previous author comment "*1818 12: Are the images free of seasonal snow?*"). Do you mean with "maximal temporal resolution" the minimum time difference in between acquisitions regarding DEM differencing and its uncertainties? Apart from DEM differencing of ALOS-PRISM to Pléiades is our minimum time difference 10 years (ALOS-PRISM to SRTM) which should be long enough for geodetic mass balance estimates . The *"… time period between the ALOS-PRISM and Pléiades data takes is only four years and should be considered as too short for reliable results.*" (page 1829, line 24 to 26). We mapped all glaciers as described in section "*5.1 Glacier area and length changes", and we* "*selected thirteen larger glaciers of different orientations*" (page 1824, line 16) for individual geodetic mass balance calculation. These were chosen regarding their size, their aspect, and the quality of the difference images within the glacier.

26: It is not clear how these ELAs have been derived, and how you can cross check it with satellite images, especially if there is a potential offset between ELA determination time and acquisition of the satellite data? Later is seems that you presume that this ELA has something to do with accumulation and ablations zones on the glaciers in your data, if I understand correctly. Why?

Reply: ELAs are based on snow line measurements that were obtained, among others, from the Chinese Glacier Inventory (cf. Shi et al., 2008). These ELAs were provided as elevation value per glacier. You are right, there might be a potential offset between the snowline measurements of Shi et al. (2008) and the acquisition time of the satellite data, particularly regarding the temporal baseline of our datasets. However, ELAs were not used for investigations on glacier variations, such as assessing snowline variations. We only used the (in case modified) ELA values of Shi et al. (2008) and others to separate individual glacier accumulation and ablation zone for later statistical gap-filling and outlier detection, described in the subsequent paragraph. This might not have been clearly enough described in the manuscript by now. We changed the paragraph from page 1824 line 25 to page 1825 line 1 as follows, referring to the separation of ablation and accumulation zone: "*These were separated by Equilibrium line altitudes (ELAs), based on the estimations of the first Chinese Glacier Inventory (cf. Shi et al., 2008). ELAs were cross-checked in ALOS-PRISM and Pléiades satellite images and adapted if necessary (see Table 3)."* Moreover, we added the following note to Table 3: "*ELAs adapted from the Chinese Glacier Inventory (cf. Shi et al., 2008)*"

17ff: If I do understand correctly you set the elevation change in the accumulation area to zero? Why? Especially in case of surging glacier one would expect to miss an important part of mass balance when doing so, even on every other glacier one could not calculate mass balances without including the accumulation area.

Reply: Following the post-processing that we previously described and for individual glacier mass balance calculations, we only set missing elevation difference values as well as outliers in the accumulation zone to zero, but we kept valid values of elevation change in the accumulation areas (Page 1825 line 11 to 15). Similar statistical gap-filling and outlier detection was, however, not possible for the entire glacierized area at Muztag Ata, which is based on individual calculations in the accumulation and ablation zone, separated by the ELA. Diverging elevation changes at similar altitudes at the glacierized area at Muztag Ata hampered such an approach that we employed for individual glaciers (page 1825 line 15 to 17). Observed glacier elevation changes were in most cases comparatively low at Muztag Ata, particularly when considering the long temporal baseline of four decades. By also taking this into account, and "s*ince no plausible statistical replacement values could be derived",* δh pixels in these accumulation zones were set*" to zero by assuming only minor elevation changes for these areas (cf.Schwitter and Raymond, 1993)"* (line 11 to 13). We subsequently defined the elevation values within the accumulation zone of the remaining glacierized area (i.e. that was not previously calculated for individual glaciers separately) to zero since we could not derive plausible replacement values for outliers and no-data pixels. Due to the large number of glaciers we assume that on average the value will not differ significantly. For individually investigated glaciers, however, we kept valid values of elevation difference in the accumulation area and set only outliers and missing values to zero, by considering the entire glacier accumulation area.

20: In case this is a section on results, I clearly see the penetration depth in a methods or data section.

Reply: Since this is still a section on methods about how we handled SRTM penetration depths, we would keep it at this place.

1826: 6: If this is a section on result, basic explanations of how to measure velocities should be part of a methods section.

Reply: Similar as in case of the previous author comment is this still a section on methods on how we measured velocities.

16 ff either present first the eq. 1 and explain the symbols or eq 2 and the symbols, but do not mix it.

Reply: Normally we would not mix equations, but in this case are the same two symbols (d_range and d_azimuth) part of both equations, so it would be difficult to explain it separately. Moreover, both equations together present the surface dynamics, in term of magnitude and direction. Practically, the offsets in range (d_range) and azimuth (d_azimuth) are saved as complex numbers (offset = d_range + i d_azimuth). Hence it's more understandable if these equations are written in such a way.

21: Section 6 is important, but parts of it are spread all over the text. The discussion of the uncertainties should be point by point, and the results of every step on the geodetic mass balance should be summarized at the end. In the current version, important sources of uncertainty are not discussed, and partly the quantification is missing.

Reply: We are not sure if we correctly understood this comment. This is a chapter about methods on how we estimate uncertainties in our results, which is based on well established approaches (see citations). We do not see that the uncertainties of our results are spread all over the text (do you mean the entire manuscript or specific sections?). We also think that this section is well structured, by presenting in three paragraphs the uncertainties of area change, then of geodetic mass balance, and finally of glacier surface velocities. Moreover, we think that we address in this chapter all significant uncertainties that are affected with our datasets. In case, could you please precise which important sources of uncertainties are not mentioned, and what could you be improved in this chapter? We agree and made the discussion of uncertainties more quantitative. This discussion is presented in chapter "8.5 Uncertainties of geodetic mass-balances from optical data" (see also later comment). We modified this section to a large extent without becoming speculative about uncertainties that are difficult to quantify.

1827: 21: The term mass balance rate is not very clear. The discussion of the effect of hole filling and skipping accumulation areas is missing.

Reply: We added "annual" to this term to address for the annual rate. We did not skip accumulation areas in our mass balance calculation, but we set no-data pixels and outliers in accumulation areas to zero, since no (statistical) replacement values could be estimated (see previous comments). We hereby assume only minor elevation changes in the accumulation area (cf. Schwitter and Raymond, 1993), and discussing the effect of varying elevation changes would be rather speculative. Please refer to section "5.2.1 Outlier detection and gap-filling" regarding our hole filling approach. On page 1824, line 27, to page 1825, line 1, we also mention well that "*Gap-filling by zero in glacier accumulation zones is a consequence of lacking statistical alternatives, but might induce biased estimates in volume change*".

1828: I do not completely understand the difference between the glacier variation chapter and the results chapter.

Reply: Chapter "*5 Assessment of glacier variations*" is a chapter on methods for specific glacier calculations, following the more general methodological chapter "*4 Data processing*" for previous data pre-processing. This methodological part as well as the chapter about uncertainties follows the chapter on results ("*7 Results*").

5 ff: This collection of numbers is nearly unreadable; the table does its job. I would rather see here some text.

Reply: We agree and we modified the text to make it more readable. We now provide an additional table (Table 3) to present the glacier length changes of all glaciers that have mass balance estimates instead of summarizing only some of them in the text of this section. The text of this section was re-arranged, making it now shorter and easier to read. Moreover, we added some additional information with a sentence in which we assume that Kuokuosele Glacier and possibly Kuosikulake and G075075E38189N Glacier might be in a surging process (see previous comment of reviewer #1).

25: What do you mean by steep tongue? Possible not an average slope or something like that?

Reply: It can be seen in our Pléiades data that the front of these glacier tongues is quite steep, which is proven by the calculated slope of its derived DEM. This is particularly visible in the hillshade of Figure 2a for Kuokuosele Glacier.

1829: 1: This should be GEODETIC mass balance

Reply: We changed the title of this chapter to "*7.2 Geodetic glacier mass-balance*".

26: Seem to fit is not very precise, especially as it is not clear to what.

Reply: We changed "*determined mass-balance changes are well in line with previous measurements*" on line 27 to "*the characteristics of surface elevation changes continue well in line with our results from other periods*."

1830: 3: We all know that this assumption is not valid, so what is the sense of the extrapolation? Would be nice to have the velocity map.

Reply: We already provided a velocity map in Figure 3, and mentioned a reference at this position. We provided the extrapolation to easily compare with other studies that employed similar annual extrapolations (e.g. Yan et al. (2013a), Yang et al. (2013), Zhou et al 2014). However, you are right that the way it was written might be irritating, and we now changed the sentence as follows: "This corresponds to a maximal flow of 70m per year if a similar flow throughout the year would be assumed". We moreover added a second annual extrapolation for "15cm per day(~55 m a^{-1})" to allow for easier comparison.

1831: 5: Geodetic mass balances

Reply: We would – in this case – keep the title as is ("*8.2 Glacier mass-balances*"), since we here discuss our geodetic mass balance results with other non-geodetic mass balances. Moreover, we discuss until now unpublished in-situ mass balance data and compare it with our results.

10 ff: I find the wording a bit confusing, and think it could help to add either direct or geodetic to the mass balance results. Is there any possibility to present the various results, periods, methods, authors and regions in a table?

Reply: P1831 L10ff refers to direct measurements in the field published by Yao et al. (2012), with some extended measurements that were by now not published. Please see to this regard our new figure showing the cumulative vs. in-situ measured mass balance for Muztag Ata Glacier (G075058E38248N) and the entire massif. We mention well that these are direct measurements from measuring stakes, and in the last sentence of the paragraph we conclude that "*the in-situ data is on average slightly lower but in tendency in good agreement with our geodetic estimations*". In the subsequent paragraph we also think that we correctly address the measurement base. In consideration of the large number of figures (7 figures) and tables (5 tables) in this manuscript we decided not to provide an additional figure or table to present the various results, periods, methods, authors and regions. Compared to the initial submitted manuscript we have by now one additional table (glacier length changes) and two additional figures (split of Figure 2 in two separate figures and an additional figure showing the hypsometry as well as the cumulative mass balance). Presenting the results of other cited references would also be rather complicated since they cover different areas at different scales, as well as different time periods.

1832 7: Fedchenko 20: could also be the case that a surge type glaciers stores mass in the accumulation are, despite mass loss at a tongue. So basically what happens at one single part of the glacier never can give an indication on total mass balance.

Reply: We fully agree. However, the volume loss mentioned for Fedchenko considers all parts of this glacier (see Lambrecht et al. 2014).

23: terminus position I suppose

Reply: Yes, terminus position, we added "terminus" at this text position.

1833 9: What is the toe? IS this tongue?

Reply: Toe was here used in the context of tongue. We replaced toe by "terminus", since the word "tongue" was already used quite often.

27: Why opening here the field of Holocene oscillations? Maybe better in the introduction?

Reply: As also suggested by the first reviewer, we moved this paragraph to the introduction.

1834

5ff: I do not understand the sentence with ablation in summer and why we find it here. The next sentences on the climate at 5910 m is a clear contradiction to the introduction, with only one station above 3000 m located close to the study site. This climate data would rather fit into the climate section before – why is it placed here? Lines 5 to 19 are either rather speculative or fit into the climate section.

Reply: We well cited the references of Seong et al. (2009a, b) regarding this and the subsequent sentence, these are not our results, but part of literature discussion. We agree that this is a speculation and therefore also write "*this might be one of the reasons…*" But we think it is valuable to discuss here the possible reasons for the balanced budget based on existing findings and the literature. These paragraphs fit, hence, well in the discussion section "glaciers response to climate".

19-21: I presume the colder years are too few to cluster in a period. It is unclear which normal period you refer to when classifying these years as 'cooler'. Cooler than what? And how much? And how large have the precipitation changes been?

Reply: This information was cited from Shangguan et al. (2006), please see also the relevant response to a similar comment of the first reviewer: Shangguan et al. (2006) do unfortunately not provide further data, expect of an additional climate diagram from Taxkorgan meteorological station. We could not find further information to better characterize these "cooling periods", and had to rely on the following information of Shangguan et al. (2006): "*This time-span included three cold periods: 1961–68, 1973–77 and 1985–93.*", and "*However, some glacier advances might be a response to the three periods of cooling and the increase of annual precipitation…*"

21 ff: We have just gone through a chapter on uncertainties, so that we do not want to go back to this once more. In any case, the impact on mass balance is not discussed!

Reply: The previous chapter on uncertainties ("*6 Uncertainties of glacier variations*") was a methodological explanation on how we estimated uncertainties in our results. This chapter "*8.5 Uncertainties of geodetic mass-balances from optical data*" now discusses uncertainties that might have an impact on our geodetic mass balance results, and demonstrates that our results are coherent and in line with what we would expect. We think this discussion is well placed here, and that the most import impacts are discussed. We, however, agree that this section could be more quantitative to some extent (see also previous comment), and we, hence, considered some modifications to this regard at this section ("8.5 Uncertainties of geodetic mass-balances from optical data", see also previous comments).

1835: 13: This would fit in a metheod section, or in the chapter on penetration depth.

Reply: We already presented how we considered for SRTM penetration depth and how we corrected it in the methods chapter "*5.2.2 SRTM-3 C-band radar penetration*". This is now a discussion chapter regarding penetration of the SRMT C-band beam, previous approaches of its correction, and how it affects our results.

1836: 24: Please give also the second period.

Reply: This is probably referring to the previous sentence *" …are slightly but insignificantly negative before 1999 (…) and positive afterwards (…).*"? If we understand right, we address both periods in the sentence of P1836 L24: "*This might still result from an eventually underestimated SRTM-3 C-band penetration into snow and ice*". Additionally, we address a possibly wide-regional "positive anomaly" for the first period, which we would not confirm for the second period: "*Slightly positive observed budgets after 1999, however, could possibly reflect a regional-wide positive anomaly with increasing snow accumulation from strengthening westerlies.* ".

Table 3: please organize the last column similar to the previous one, the -+ in one line. How is the ELA calculated?

Reply: The last column is currently organized so that the last +- sign in the parentheses is in one line. We did not succeed to manipulate the Latex document in a way that the values before the parentheses are also in one line, maybe this could be considered for final typesetting before publication. The ELA origin is presented in section "*5.2.1 Outlier detection and gap-filling*", please see also previous comments related to the same ELA data. To avoid confusion and to address for similar comments of the first reviewer, we now mention in a remark of this table its origin "*ELAs adapted from the first Chinese Glacier Inventory (cf. Shi et al., 2008)".*

Table 4: See main remark on periods (Main remark: The presentation of the periods is also confusing, I would recommend to present the total period 1973-2013 and the subperiods (1973-1999, 1999-2009, 2009-2013).. Annual mass balance: Should be mean annual geodetic mass balance.

Reply: An inappropriate organization of the periods was also remarked by the first reviewer, and we improved the periods accordingly in the table. We hereby particularly tried to follow your suggestion by first presenting the total periods (1973–2013(and 1973–2009) and then the sub-periods in a chronological way (see author responses to the comments of the first reviewer). In the title, we now mention "*geodetic mass balance rates*". We would not add "annual" since this is already implied by "rates".

Figure 1 : Stations lacking (Main remark: … and the location of the climate measurements should be evident from Figure 1)

Reply: We improved this figure accordingly to the comments of the first reviewer. Since no climate measurements were taken in this study, there is need for such visualization in this figure.

Figure 3: Below T3 some stripes are visible – is that an artifact?

Reply: As TSX is very high resolution data, it details the precise displacement offset results. However, to ensure the possible artifact, especially in featureless accumulation zone, we used SNR threshold of 4.0 and discard the possible decorrelated offsets (see chapter "4.4 SAR image co-registration").

Figure 4: The ELA is a calculated value, and could not be indicated in an image as line as done here. Is this a snow line, or a contour line of elevation? What is the black area?

Reply: We simply used the ELA to separate accumulation from ablation area needed for statistical gap-filling and outlier handling, as presented in section "5.2.1 Outlier detection and gap-filling" (please see also previous comments related to similar questions). The origin of the ELA is also described in this chapter. We now included in the figure captions that the ELA was adapted from Shi et al. (2008), as in case of Table 3. To which black area are you refereeing to in Figure 4? Do you mean the shaded area from the hillshade in case of steep south-east exposed slopes?

Figure 5: Where does the volume loss outside the glaciers come from?

Reply: The visible elevation change stems from the uncertainty of the utilized DEMs. It is particularly observed when differencing with the KH-9 Hexagon DEM and reflected in higher NMAD values (see Table 2). We already mentioned this in the discussion at P1835 L1ff: "*KH-9 Hexagon shows high noise at low-contrast terrain in its DEM, but much better results at debris-covered and crevassed glacier surfaces.*". To this sentence, we added *"(reflected in higher NMAD values)*" after "*in its DEM…*".

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Four decades of glacier variations at Muztag Ata (Eastern Pamir): a multi-sensor study including Hexagon KH-9 and Pléiades data

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Abstract

~~Recent~~ Previous mass balance measurements ~~indicate~~ indicated a slight mass gain at Muztag Ata in the Eastern Pamir, contrary to the global trend. We extend these measurements both in space and time by using remote sensing data and present four decades of glacier variations in the entire mountain massif. Geodetic mass-balances and area changes were determined at glacier scale from stereo satellite imagery and derived Digital Elevation Models (DEMs). This includes Hexagon KH-9 (year 1973), ALOS-PRISM (2009), Pléiades (2013) and Landsat 7 ETM+ data in conjunction with the SRTM-3 DEM (2000). In addition, surface velocities of Kekesayi Glacier, the largest glacier at Muztag Ata, were derived from TerraSAR-X amplitude tracking (2011). Locally, we observed strong spatial and temporal glacier variations during the last four decades, which were, however, on average not significant for the entire massif. Some south-west exposed glaciers fluctuated or advanced, while glaciers with other aspects rather experienced continuous shrinkage. Several glaciers such as Kekesayi indicate no ~~visual~~ measurable change at their frontal position, but clear down-wasting despite mostly thick debris coverage at low altitudes. The surface velocity of this largest debris-covered glacier of the massif reach up to 20 cm per day, but its distal part of the tongue appears to be stagnant. The low velocity or even stagnancy at the tongue is likely one reason for the down-wasting. On average, the glaciers showed a small, insignificant shrinkage from $274.3 \pm 10.6\,\mathrm{km}^2$ in 1973 to $272.7 \pm 1.0\,\mathrm{km}^2$ in 2013 ($-0.02 \pm 0.1\,\%\,\mathrm{a}^{-1}$). Average mass changes in the range of $-0.03 \pm 0.33\,\mathrm{m\,w.e.\,a}^{-1}$ (1973–2009) to $-0.01 \pm 0.30\,\mathrm{m\,w.e.\,a}^{-1}$ (1973–2013) reveal nearly balanced budgets for the last forty years. Indications of slightly positive trends after 1999 ($+0.04 \pm 0.27\,\mathrm{m\,w.e.\,a}^{-1}$) are confirmed by in-situ measurements.

1 Introduction

~~Muztag Ata (7546 m a.s.l.) and Kongur Shan (7719 m a.s.l.) form a massif of anomalously high topography which reaches ∼1500 to 2000 m higher than any neighboring peak in the Eastern Pamir. These mountains are located west of the Taklamakan Desert in one of the driest glacierized areas of China and one of the coldest environments in these low- and mid-latitude regions. The glaciers are seasonal to long-term water resources and play an important regulating role for downstream freshwater supply. Moreover, they act as valuable indicators of a changing climate (Seong et al., 2009b; Yang et al., 2013; Vaughan et al., 2013).~~

~~From 2003 to 2009 the glaciers of~~ The glaciers of High Mountain Asia revealed an average mass loss at $-26 \pm 12\,\mathrm{Gt\,a^{-1}}$ from 2003 to 2009, which, however, is affected by strong regional variations (Gardner et al., 2013). Heterogeneous glacier mass balances in Pamir and Karakoram are confirmed at least for the last decade (Bolch et al., 2012; Kääb et al., 2012; Yao et al., 2012; Gardelle et al., 2013). Glaciers in the Pamir continued to retreat and shrink on average, ~~but at the same time numerous~~ while several glacier surges were observed ~~(Kotlyakov et al., 2008; Unger-Shayesteh et al., 2013). Slight~~ at the same time (Kotlyakov et al., 2008; Unger-Shayesteh et al., 2013). Since 1999, slight mass gain of $+0.10 \pm 0.16\,\mathrm{m\,w.e.\,a^{-1}}$ was measured in the Central Karakoram, and of $+0.14 \pm 0.13\,\mathrm{m\,w.e.\,a^{-1}}$ in West Pamir using SPOT and SRTM DEMs (Gardelle et al., 2013). However, Gardner et al. (2013) and Kääb et al. (2015) found presumably negative mass budgets in Pamir using ICESat laser altimetry data ~~.~~ from 2003 to 2008/09.

Regional glacier variations might be a response to changing atmospheric circulation patterns. The Indian monsoon is quite likely to weaken and strengthening westerlies come along with an increase of precipitation (Yao et al., 2012). In Xinjiang Province (North-West China), from 1961 to 2008 both mean annual temperature and precipitation increased per decade by $+0.3\,^{\circ}\mathrm{C}$ and $+7.4\,\mathrm{mm}$ (Zhang et al., 2012). Warming was most observed at altitudes between 4800 m and 6200 m a.s.l. which ~~include~~ affects the ablation zones of almost all glaciers on the Tibetan Plateau ~~(Yao et al., 2012; Zhang et al., 2012; Qiu, 2014).~~

(Yao et al., 2012). One of the driest glacierized areas of China and one of the coldest environments in these low- and mid-latitude regions forms the easternmost edge of the Pamir (Shangguan et al., 2006; Zhou et al., 2014). Its glaciers are seasonal to long-term water resources and play an important regulating role for downstream freshwater supply. Moreover, they act as valuable indicators of a changing climate (Seong et al., 2009b; Vaughan et al., 2013; Qiu, 2014).

~~The main aim of this paper is to fill a knowledge gap, since detailed glaciological studies in the Pamir are scarce and show ambiguous results (Unger-Shayesteh et al., 2013). We investigated~~ In this study, we investigate four decades of glacier variations at Muztag Ata~~by use of~~, situated in the most Eastern Pamir west of the Taklamakan Desert. Its glaciers oscillated considerably throughout the Late Glacial and Holocene when the glaciation style has changed from an expanded ice cap to deeply entrenched valley and cirque glaciers. This is possibly reflected by responding to Northern Hemisphere climate and/or topographic constraints (Seong et al., 2009b, a). We used historical and state-of-the-art remote sensing datasets such as Hexagon KH-9 and Pléiades for ~~the period 1973–2013~~a detailed reconstruction from 1973 to 2013. The main aim of this research is to fill a knowledge gap, since detailed glaciological studies in this region are scarce and show ambiguous results (Unger-Shayesteh et al., 2013). A further aim is to improve the knowledge of the reaction of debris-covered glaciers in this region by taking Kekesayi Glacier as an example. Therefore surface velocities were measured by TerraSAR-X amplitude tracking and compared to surface elevation changes.

2 Study area

Muztag Ata (38°17′ N, 75°07′ E, 7546 m a.s.l., Fig. 1) is situated at the easternmost end of the Pamir in Xinjiang Province, China~~(Fig. 1)~~. This massif of anomalously high topography reaches ∼1500 m higher than any neighboring peak in the Eastern Pamir (Seong et al., 2009b; Yang et al., 2013). Its cold valley glaciers are of the extremely continental type and accumulate snow mostly in winter

~~(Shih et al., 1980; Maussion et al., 2014)~~(Shih et al., 1980; Maussion et al., 2014; Zhou et al., 20 A roughly north-south trending high ridge and watershed divides the massif into a ~~western~~ windward area with small valley glaciers exposed towards the westerlies and an eastern leeward part with higher gradients. Glacier meltwater drains southwards to the Taxkorgan River, a tributary of the Yarkant River, and northwards to the Gezhe River, being a tributary of the Kaxgar River. With a length of ∼18 km and an extent of 86.5 km^2 is the debris-covered Kekesayi ~~(G075225E38255N)~~ Glacier by far the largest glacier of this massif (Shangguan et al., 2006; Seong et al., 2009b, a; Yang et al., 2013).

The cold and semi-arid continental type climate of this region is principally influenced by mid-latitude westerlies (Peel et al., 2007; Seong et al., 2009a; Yao et al., 2012). The Taxkorgan meteorological station (37°46′ N, 75°14′ E, 3091 m a.s.l.), situated ∼50 km south of Muztag Ata, is the only station on the east Pamir Plateau above 3000 m a.s.l. (Shangguan et al., 2006). From 1957 to 2010 the mean annual temperature at this station was measured to be at +3.4 °C, the mean summer temperature at +15.1 °C (June–August), and the mean annual precipitation at ~~70.2~~∼70 mm (Yan et al., 2013b; Yang et al., 2013). The ~~climate has been becoming warmer and wetter (Shi et al., 2007; Qiu, 2014). The summer temperature rose by +0.7~~mean annual precipitation to the glacier accumulation zone at Muztag Ata was measured to be ∼ ~~°C from 1957 and 2000 while precipitation slightly increased at the same time (Shangguan et al., 2006; Tian et al., 2006; Yao et al., 2012). In summer 2003 an ice core of 41.6~~300 ~~m in depth was drilled at 7010~~mm at 5910 m a.s.l. ~~at Muztag Ata~~ (38°~~17~~42′ N,75°~~06~~01′ E). ~~Its isotope variations are in good agreement with annual air temperature changes of the close-by Taxkorgan meteorological station. However, starting in the 1990s, a more rapid warming trend of +2.0 to +2.4~~Summer precipitation is estimated to only account for 30 ~~°C per decade was observed, compared to Taxkorgan station measures at +0.18°C per decade (Tian et al., 2006).~~ % of the annual total (Seong et al., 2009b, a).

3 Data

Imagery was acquired under the premise of having a minimum cloud and snow cover. Data is referenced to WGS-84 at UTM zone 43N and to the EGM-96 geoid. Stereo imagery employed for DEM extraction is summarized in Table 1 and described below.

3.1 Hexagon KH-9

Hexagon KH-9 was a photographic satellite surveillance system flown during 20 missions ~~(1201–1220)~~ from June 1971 to April 1986 by the United States (~~US~~mission number: 1201–1220). During 12 missions (1205–1216) approximately 29 000 photographs were acquired with its mapping camera and declassified in 2002 (Burnett, 2012). It is assumed that for the KH-9 mapping camera a similar design like for the NASA Large Format Camera (LFC) of 1984 was used (cf. Mollberg, 1981). This is a 23 × 46 cm frame format camera with 30.5 cm focal length. Photographs contain four fiducial marks with 1058 reseau-crosses and provide ground coverage of 250 × 125 km at 6–9 m resolution. Imagery was returned in single buckets of films from 171 km operational altitude. DEM extraction is made possible from triplet stereo-coverage with 70 % overlap and a base-to-height (b/h) ratio of 0.4 (Surazakov and Aizen, 2010; NRO, 2011; Burnett, 2012).

KH-9 photographs were scanned in two segments at 7 microns (3600 dpi) with about 1 cm of overlap and stored in 8-bits TIFF file format. Four overlapping black-and-white scenes without any geo-corrections were purchased by the ~~US~~ United States Geological Survey (USGS). Imagery with frame numbers 16–19 was recorded on 4 August 1973 during mission 1206-5.

3.2 Pléiades

The high resolution Pléiades ~~is an optical high resolution earth observation satellite system developed as part of the intergovernmental ORFEO agreement between~~ satellite system was developed by France and Italy. Pléiades 1A was launched in December 2011, followed by Pléiades 1B in December 2012. The spatial resolution of the panchromatic channel is resampled to 0.5 m with a pixel depth of 12-bits at acquisition. It provides an image swath of 20 km at nadir by flying at an operational altitude of 694 km. Pléiades offers in-track standard as well as tri-stereo capability with an additional quasi vertical image~~for the extraction of DEMs~~. The location accuracy was measured to be 8.5 m for nadir-looking images of Pléiades 1A and 4.5 m of Pléiades 1B (Astrium, 2012; Gleyzes et al., 2012; Berthier et al., 2014).

We purchased a level-1A stereo bundle mosaic of three images that cover an area of 663 km^2. The image file recorded on 20 June 2013 covers about two-thirds of the eastern part. The image of 19 June 2013 covers the western third~~and the image of 3 August 2013~~, except of some small cloud covered areas in the south-west ~~.~~ that are covered by the image of 3 August 2013. Imagery was provided in GeoTIFF file format with b/h-ratios ranging from 0.2 to 0.3.

3.3 ALOS-PRISM

The Japanese satellite system ALOS (Advanced Land Observing Satellite) ~~was a Japanese satellite system which~~ operated from January 2006 to April ~~2011.~~ 2011 at an operational altitude of 692 km. Its PRISM (Panchromatic Remote-Sensing Instrument for Stereo Mapping) optical sensor consisted of three independent high-resolution panchromatic radiometers. These provided in-track triplet-coverage from backward-, nadir- and forward-looking directions. The b/h-ratio is up to 1.0 when using forward- and backward-looking views with an inclination of $\pm$23.8° from nadir. ~~Imagery was recorded in-track from the same orbit at an operational altitude of 692 km.~~ It offered 2.5 m spatial and 8-bits radiometric resolution with a swath width of 35 km in triplet mode. ~~High-resolution DEMs can be extracted at b/h-ratios of up to 1.0 when using forward- and backward-looking views.~~ The absolute geometric accuracy amounts to 8.1 m for nadir-looking images and 9.3 m for forward- and backward views (Takaku et al., 2007; JAXA, 2008; Tadono, 2009).

We purchased a radiometrically calibrated triplet mode scene at level-1B1 in CEOS file format. The data was acquired on 10 September 2009 and provided with Rational Polynomial Coefficients (RPC)~~, acquired on 10 September 2009.~~ .

3.4 Landsat

Glacier delineation for the year 2000 and horizontal measurements of Ground Control Points (GCPs) is based on imagery of the Landsat Enhanced Thematic Mapper 7 (ETM+). Orthorectification to 15 m pixel size for the panchromatic and 30 m for the multispectral band was conducted by use of the Global Land Surveys (GLS2000) dataset. Terrain-corrected imagery at level-T1 was provided by USGS, acquired on 11 September 2000.

3.5 Shuttle Radar Topography Mission (SRTM)

A near-global DEM between 60° N and 57° S was acquired during the Shuttle Radar Topography Mission (SRTM) with C- and X-band SAR from 11 to 22 February 2000. This served as vertical reference and for co-registration of all extracted elevation datasets. We used the hole-filled SRTM-3 version 4.1 at EGM 96 orthometric heights with 90 m pixel resolution. Elevation data and a mask to identify hole-filled terrain were provided by the Consultative Group for International Agricultural Research (CGIAR) (Hoffmann and Walter, 2006; Reuter et al., 2007; Jarvis et al., 2008).

3.6 TerraSAR-X

TerraSAR-X is a German X-band radar satellite launched in June 2007. Data is available in Spotlight, Stripmap and ScanSAR modes at all achievable polarization arrangements (HH, HV, VV and VH). We obtained two Stripmap mode images acquired on 10 August and 1 September 2011 during the descending pass of the satellite. Image extent is 19.7×21.2 km on ground with a pixel spacing of 0.9 m in slant range (signal direction) and 3.0 m in azimuth (flight direction). The incidence angle at the scene center is 44.3°. The data was delivered by the German Aerospace Center (DLR) in Single Look Complex (SLC) format (Herrmann and Bottero, 2007; Eineder et al., 2008).

4 Data processing

4.1 KH-9 image pre-processing

We resampled the KH-9 photograph segments to 14 microns for simpler data handling, in consideration of the large file size. Prior to DEM extraction, it was necessary to reconstruct the original conditions of image geometry at the time of film exposure. This is indispensable to obtain accurate elevation information from KH-9 stereo photographs. Film distortions evolved over time due to duplication and storage during almost four decades. Such distortions were corrected by evaluating its reseau grid overlaid in the photograph which consists of 1058 crosses at 1 cm spacing. The original image geometry was reconstructed by a second-order bilinear interpolation. Based on a Python tool developed by Pieczonka et al. (2013), we automatically determined all reseau-crosses in the imagery and resampled them back to their initial reference positions. Reseau-crosses were expected to later confuse terrain extraction and were therefore eliminated using bicubic interpolation from surrounding pixels (cf. Pieczonka et al., 2013). Prior to mosaicing, Wallis filtering with 51×51 pixels window size and histogram equalization was finally conducted for contrast enhancement (cf. Surazakov and Aizen, 2010; Pieczonka et al., 2013). In most scanned photographs unfortunately there exist no fiducial marks. Hence, we assumed the image principle-point as identical with the central reseau grid coordinate of both corresponding mosaiced segments. This position was also considered as origin of initial reference for image geometry reconstruction and is therefore not affected by resampling. Besides the film distortion, also a rotation component appears around the principle-point in the distortion vectors. This probably originates from an occasionally slightly rotated scan of a film segment (Fig. ~~??~~2) (Holzer et al., 2012).

4.2 Terrain extraction

4.2.1 Ground Control Points

Measuring Ground Control Points (GCPs) proved to be challenging due to the remoteness of the region and the lack of accurate ground truth data. GCPs were ~~ideally~~ situated at stable and plain terrain, ideally close to laser altimetry measurements of the Ice Cloud and Elevation Satellite (ICESat) which proved to be a valid elevation source (Nuth and Kääb, 2011). The SRTM-3 DEM served as z-reference ~~, if~~ for one third of the GCPs, since no ICESat information was available. x and y coordinates were measured from a pan-sharpened Landsat 7 ETM+ scene dating from 2000. All GCPs were finally cross-checked in Google Earth™. Finding suitable GCPs was particularly difficult for Hexagon KH-9 due to its long temporal baseline when anthropogenic objects like road intersections and houses did not exist back in 1973. We measured ~~20~~18 GCPs for KH-9 Hexagon, ~~but two of them showed high residual offsets and were subsequently set as check points.~~ ALOS-PRISM is covered by 6 GCPs and the Pléiades mosaic by 11 GCPs with at least 4 GCPs per scene.

4.2.2 DEM extraction

DEM extraction from Hexagon KH-9 photographs is based on a non-metric frame camera model using the Leica Photogrammetry Suite 9.2 (LPS). Inner orientation settings with 30.5 cm focal length were defined as fix for triangulation, but we used Brown's physical model to compensate for unknown lens and ~~eventually~~ potentially remaining film distortions. The principle-point offset was determined from the central reseau-cross coordinate to the mid-point of the image, which is defined by its extent. Due to the lack of ephemeral or analogue metadata information is the exterior orientation solely based on 18 measured GCPs, by taking in consideration of the earth curvature. The RMSE of bundle block adjustment proved to be 0.49 pixels. The DEM was extracted with adaptive automatic terrain extraction (ATE) from triplet stereo coverage to a resolution of 30 m.

DEM extraction from ALOS-PRISM and Pléiades stereo imagery was performed using the Orthoengine of the PCI Geomatica 2013 software package. We used its *Rational Functions* model to derive DEMs with first-order RPC adjustment from attached ephemeral data and the measured GCPs. The GCP residuals of bundle block adjustment proved to be 0.36 m in x and 0.34 m in y direction for ALOS-PRISM as well as 0.18 and 0.12 m for Pléiades, respectively. Wallis filtering was applied to improve the image matching process. The DEM of ALOS-PRISM at 10 m resolution is based on epipolar pairs from the backward- and nadir- as well as from the nadir- and forward-looking views with their highest obtained score. For each of the three Pléiades scenes we derived a very high-resolution DEM at 1 m resolution from their stereo views (Fig. ??). 4). The DEM of ALOS-PRISM does not cover the westernmost part of Muztag Ata, and the DEM of Pléiades is affected by several gaps due to clouds in the south-west.

4.3 DEM post-processing

4.3.1 Clean-up of DEM areas with low-quality

All DEMs including SRTM-3 were resampled to 30 m resolution by cubic convolution and to a common raster grid extent for exact cell alignment. PCI Orthoengine provides an additional image which represents the stereo matching score for each extracted DEM pixel. We applied a threshold of 0.7 to exclude elevations of poor accuracy in the DEMs of ALOS-PRISM and Pléiades. The thematic point status image of LPS showed that correlation scores of most calculated DEM points from KH-9 Hexagon (76 %) were ranging from 0.5 to 0.7. Beside these elevations of fair quality were 17 % of good and 7 % of excellent accuracy, with coefficients higher than 0.85. Large DEM parts, however, consisted of clearly erroneous elevations despite a fairly good indicated quality. This was particularly observed in case of poor contrast in the KH-9 imagery. We identified such elevations by both its hillshade and its difference image relative to SRTM-3 and set them to no-data.

4.3.2 DEM co-registration

Horizontal DEM co-registration to SRTM-3 was conducted ~~by an analytical approach which minimizes~~ analytically by minimizing the elevation error based on the relationship between elevation difference and aspect (cf. Nuth and Kääb, 2011). The approach was based on a routine implemented in Python programming language by Pieczonka et al. (2013). For each DEM we calculated its difference image relative to SRTM-3 by excluding non-stable terrain such as (rock) glaciers, ice-cored moraines and lakes. To allow for the slope dependency of the method, we excluded all terrain below a slope of 10°. The initial spatial resolution of SRTM-3 (90 m) is coarser than that of the derived DEMs. This can lead to resolution-implicated biases at topographic extremes where curvature is strong (cf. Paul, 2008; Gardelle et al., 2012a). To consider for outliers and such curvature effects, we first bounded valid pixels of DEM differencing to their 5 and 95 % quantiles (cf. Hoffmann and Walter, 2006). Subsequently we excluded all elevation differences outside of its two-fold 1.5 times interquartile range (cf. Pieczonka et al., 2013). The determined horizontal shifts were iteratively reduced until for each DEM an accuracy of at least 1 m in x and y direction in respect to SRTM-3 was reached.

Spatially-varying elevation biases were corrected by two-dimensional trend surfaces in off-glacier regions (cf. Bolch et al., 2008; Pieczonka et al., 2011). These were calculated from DEM difference images and reduced the mean height-offset relative to SRTM-3 on stable terrain to zero. Quantile analysis was employed in a similar way as for horizontal alignment to take curvature effects into account. The vertical accuracy of SRTM-3 decreases in case of steep terrain, and we thus only considered flat areas until a slope angle of 10° (Falorni et al., 2005). Offsets were usually apparent as tilts and therefore corrected by linear surfaces. The DEM of ALOS-PRISM indicated a slight second-order polynomial trend offset. All three extracted DEMs of Pléiades were mosaiced to one single file after co-registration.

4.4 SAR image co-registration

TerraSAR-X data was processed using GAMMA Remote Sensing software. Data was converted to software-readable SLC format which contains the amplitude (backscatter) and phase information from the signal interaction with the Earth surface. We defined the image of 1 September 2011 as slave and co-registered it at sub-pixel accuracy to the master image of 10 August 2011. Orbital offsets and ionospheric shifts were corrected by means of amplitude correlation, determined over well distributed windows of 128 $\times$ 128 pixels. In selected windows the bilinear offset polynomial for image registration was calculated by employing a threshold of 4.0 from the signal-to-noise ratio (Strozzi et al., 2002).

5 Assessment of glacier variations

5.1 Glacier area and length changes

KH-9 Hexagon, ALOS-PRISM and Pléiades imagery were ortho-rectified by use of DEMs generated from their own stereo data. ~~All glaciers~~ Glaciers and ice divides were manually mapped using the very high-resolution (0.5 m) Pléiades ortho-image mosaic and finally cross-checked with Google Earth™. Glacier mapping, particularly in case of debris coverage, was also based on a hillshade from the Pléiades DEM at 1 m resolution and derived morphometric parameters. The generated inventory representing the glacier situation in 2013 was afterwards manually adjusted to the extents of the years 1973, 2000 and 2009. This is based on the ortho-rectified KH-9 Hexagon (6.0–9.0 m), pan-sharpened Landsat ETM+ (15 m) and ALOS-PRISM (2.5 m) datasets. Changes in glacier length were distinguished along their central flow line.

5.2 ~~Glacier~~ Geodetic glacier mass-balance

Geodetic glacier mass-balances are based on Δh pixels by differencing elevations of older dates (e.g. KH-9 Hexagon) from more recent elevations (e.g. Pléiades). Difference images were generated for all possible DEM combinations of KH-9 Hexagon (1973), SRTM-3 (1999), ALOS-PRISM (2009) and Pléiades (2013). ~~All three extracted DEMs of Pléiades were mosaiced to one single file after co-registration. The DEM of ALOS-PRISM does not cover the westernmost part of Muztag Ata, and the DEM of Pléiades shows several gaps in the south-west due to clouds.~~ SRTM voids are particularly observed at steep slopes and mountain ridges, while most of the glacier areas consist of non-interpolated data. We restricted mass-balance calculations to the original SRTM-3 surfaces and excluded gap-filled voids because of high inaccuracies (cf. Kääb et al., 2012). On stable terrain slight offsets in mean height were induced while differencing DEMs which were both extracted from optical data. The biases were below 1 m and resulted from co-registration of all DEMs exclusively to SRTM-3. Offsets were corrected to keep off-glacier elevation differences for all DEM combinations in their mean at zero. We selected thirteen larger glaciers of different orientations to calculate their thickness and volume change as well as their mass-balance by assuming an ice density of $850 \pm 60\,\mathrm{kg\,m^{-3}}$ (Huss, 2013). Mass change was estimated for the entire glacierized area of Muztag Ata as well by also taking the mass-balances of individual glaciers into account. The glacier size was defined by the largest extent of the correspondent mass-balance investigation period.

5.2.1 Outlier detection and gap-filling

Data gaps smaller than $0.01\,\mathrm{km}^2$ were closed by a mean filter based on surrounding Δh values. Outlier detection and gap filling of remaining Δh voids in glacier areas were employed separately for each glacier accumulation and ablation zone. These were separated by Equilibrium line altitudes (ELAs)~~are based on snow line measurements obtained from the~~ , based on estimations of the first Chinese Glacier Inventory (cf. Shi et al., 2008). ~~All~~ ELAs were cross-checked in ~~available satellite images and in some cases adapted~~ ALOS-PRISM and Pléiades ortho images and adapted if necessary (see Table 4). ELAs are also based on geometric calculations of Seong et al. (2009b) and in-situ measurements at Muztag Ata Glacier No. 15 (cf. Yao et al., 2012).

For each 25 m elevation band in the ablation zone, we restricted the minimal and maximal allowable elevation differences to its 5 and 95 % quantiles and replaced outliers with its marginal quantile values. In case of Kematulejia and Kuosikulake Glacier, this restriction was tightened to the 31.7 and 68.3 % quantiles because of higher noise. Remaining no-data gaps were filled by mean elevation differences calculated for each 25 m elevation section in the ablation zone. Poor image contrast in the snow covered accumulation zone led to high noise of Δh values and large areas without elevation estimates. Since no plausible statistical replacement values could be derived, we set missing Δh pixels to zero by assuming only minor elevation changes for these areas (cf. Schwitter and Raymond, 1993).

Elevations outside the range of the 31.7 and 68.3 % Δh quantiles of each glacier accumulation zone were considered as outliers and also set to zero. Statistical outlier detection and gap filling employed to individual glaciers were not possible for the entire glacierized area due to diverging glacier elevation changes at similar altitudes. For the remaining glacierized area, we subsequently defined a Δh threshold of $\pm$100 m for the ablation area and set all Δh pixels of the accumulation area to zero.

5.2.2 SRTM-3 C-band radar penetration

SRTM-3 C-band penetrations strongly depend on the topmost glacier surface condition. Landsat 7 ETM+ imagery recorded on 7 February 2000 shows slight snow coverage with mostly snow-free glacier tongues at Muztag Ata. In this study, we assume that SRTM-3 approximately detects the ~~ice of~~ surface at the end of the melt season in 1999. C-band penetrations were corrected separately for glacier accumulation and ablation zones based on estimates by Kääb et al. (2012). In doing so, we averaged penetration depth estimates of the three nearby and southwards situated Hindu-Kush, Karakoram and Jammu-Kashmir study sites. This results in penetration assumptions of 4.3 $\pm$ 0.9 m for firn and snow (accumulation zone) and 1.5 $\pm$ 0.9 m for clean ice ablation zones, by assuming no penetration in the case of supraglacial debris. Added offsets are positive if SRTM is representing glacier surfaces of older date (1999–2009/2013) and negative if it is of newer date (1973–1999).

There is no need for such corrections if the DEM differencing is solely based on optical data.

5.3 Glacier surface velocities

~~To determine surface~~ Surface velocities of Kekesayi Glacier ~~(G075225E38255N) we employed amplitude tracking~~ were determined by amplitude tracking that also performed well in most parts of the upper glacier area (e.g. Strozzi et al., 2002; Floricioiu et al., 2010; Rankl et al., 2014). It was not possible to retain the interferometric phase due to temporal decorrelation over 22 days. Phase-based methods such as DInSAR (cf. Goldstein et al., 1993), GInSAR (cf. Sharov et al., 2002) or double difference InSAR (cf. Floricioiu et al., 2010) subsequently failed due to low coherence. The normalized cross-correlation function was estimated in the co-registered master-slave images using 64 $\times$ 64 pixel windows. Motion in azimuth and range direction was yielded by the peak location of this function. Glacier surface dynamics were determined as,

$$d_{\text{absolute}} = \sqrt{d_{\text{range}}^2 + d_{\text{azimuth}}^2}$$

$$\delta_{\text{flow}} = \tan^{-1} \frac{d_{\text{range}}}{d_{\text{azimuth}}}$$

where d_{range} and d_{azimuth} are the motions of the glacier surface in range and azimuth directions respectively. d_{absolute} represents the magnitude of surface velocity and δ_{flow} depicts the direction of glacier flow (cf. Strozzi et al., 2002).

6 Uncertainties of glacier variations

Mapping precision of clean-ice glaciers can be roughly estimated by a one-pixel variability of glacier outlines based on the spatial resolution of its reference imagery (Bolch et al., 2010; Frey et al., 2012; Paul et al., 2013). We enlarged buffers to consider the difficult visual interpretation of debris cover and to take the high spatial resolution of some images into account. The glacier reference outlines from Pléiades of 2013 were buffered with ±1 m and the adaption from ALOS-PRISM of 2009 with ±2 m. For Hexagon KH-9 and Landsat 7 ETM+ we followed the buffer sizes proposed by Bolch et al. (2010) and used a glacier size variability of ±10 m for 1973 and of ±7.5 m for 2000. Uncertainties of glacier area and length changes are defined by the root sum squares of each error term and dominated by higher mapping inaccuracies of older datasets.

We calculated the Normalized Median Absolute Deviation (NMAD), the 68.3 and 95 % quantile to measure the vertical DEM precision of all difference images from the multi-temporal DEMs (cf. Höhle and Höhle, 2009). Similar to DEM co-registration, is this calculation based on DEM differencing by excluding non-stable terrain and by considering outliers and curvature effects (Table 2). Density of glacier ice is assumed to deviate in the range of ±60 kg m^{-3} (cf. Huss, 2013). Another influence onto DEM differencing with SRTM-3 is its penetration-depth uncertainty. This was estimated to be ±0.9 m as the highest uncertainty of the averaged penetration depth corrections of Kääb et al. (2012). The final mass-balance and volume-change uncertainties are the root of the sum of each squared error term and consist of the NMAD as well as the uncertainties of ice-density assumption and of C-band penetration depth correction if applicable. For annual mass-balance rates this is converted into water equivalent and divided by the observational years. The uncertainties of volume change are multiplied by the glacier area and converted to ice equivalent.

The uncertainty in surface velocities exhibits the imprecise matching of the glacier surface features within the search windows. We measured residual velocities at a stable and plain surface after the glacier terminus, where the channels carry the water discharge from the glacier. The RMSE was estimated over non-moving terrain of ∼5 km^2 to be ±0.58 cm per day.

7 Results

Investigated glaciers were named according to their ID in the GLIMS Database (GLIMS and NSIDC, 2005, updated 2014) (see Fig. 1).

7.1 Glacier area and length changes

For the last four decades the The glaciers at Muztag Ata showed heterogeneous variations with some fluctuating or advancing, but mostly stable or continuously retreating glacier tongues (Table 4). during the last four decades. Area and length changes are highly variable from one glacier to another, even if they are located adjacently. Several glaciers such as Kekesayi (G075225E38255N) or G075171E38163N are heavily covered by debris and did not indicate any change at their frontal position. Average glacier retreat was observed to be $-1.0 \pm 0.3\,\mathrm{m\,a^{-1}}$ from 1973 to 2013. Glacier length changes show decreasing and even positive values for later periods (Table 3). The determined overall shrinkage of $-0.6 \pm 3.9\,\%$ ($-0.02 \pm 0.1\,\%\,\mathrm{a^{-1}}$) is therefore comparably low and not significant. This corresponds to a glacier area reduction of $-1.6 \pm 10.6\,\mathrm{km^2}$ from $274.3 \pm 10.6\,\mathrm{km^2}$ in 1973 to $272.7 \pm 1.0\,\mathrm{km^2}$ in 2013. Area and length changes are highly variable from one glacier to another, even if they are located adjacently. On the one hand, for instance, retreated glacier G075233E38272N by $-250.0 \pm 10.0\,\mathrm{m}$ ($-2.7 \pm 2.8\,\%$ shrinkage), glacier G075175E38297N by $-400.0 \pm 10.0\,\mathrm{m}$ ($-2.3 \pm 2.7\,\%$ shrinkage) and glacier G075071E38240N by $-150.0 \pm 10.0\,\mathrm{m}$ ($-1.4 \pm 2.8\,\%$ shrinkage) from 1973 to 2013. On the other hand, advanced Kuokuosele Glacier (G075156E38175N) by $+150 \pm 12.5\,\mathrm{m}$ from 1973 to 2000, followed by $+340 \pm 7.8\,\mathrm{m}$ from 2000 to 2009 and by another $+130 \pm 2.2\,\mathrm{m}$ from 2009 to 2013 (enlargement of +2.1Table 4). The maximal extent of glaciation was observed to be at $\sim \pm 5000$ 2.6 %). Glacier G075075E38189N retreated by $-150 \pm 12.5\,\mathrm{m}$ from 1973 to 2000 and advanced afterwards back and even beyond its position of 1973 during the period of 2000 to 2013 (enlargement of $+3.0 \pm 5.9\,\%$). Kuosikulake Glacier (G075092E38214N) indicated a more or less stable tongue for the period of 1973 to 2000, followed by a sudden retreat of $-350 \pm 7.8\,\mathrm{m}$ until 2009 and a fast subsequent advance of $+250 \pm 2.2\,\mathrm{m}$ from 2009 to 2013 ($-0.6 \pm 2.6\,\%$ shrinkage). Kuokuoseleand Kuosikulake show steep glacier m (Fig. 3).

Three south-western orientated glaciers (Kuosikulake, G075075E38189N and Kuokuosele) show steep tongues in Pléiades which indicates that advance was still in progress in 2013 (see Fig. ~~??~~ 4 for Kuokuosele Glacier). We assume that Kuokuosele Glacier and possibly Kuosikulake and G075075E38189N Glacier might be in a surging process.

7.2 ~~Glacier~~ Geodetic glacier mass-balance

Glacier thickness change is determined by difference images from DEMs of Pléiades and ALOS-PRISM to SRTM-3 for 1999 to 2009/2013 (Fig. 8), Pléiades and ALOS-PRISM to KH-9 Hexagon for 1973 to 2009/2013 (Fig. 6) as well as SRTM-3 to KH-9 Hexagon for 1973 to 1999 (Fig. ~~??~~7). Difference images of multiple time periods show clear temporal variations of ice thickness change and movement, which is particularly evident for advancing or fluctuating glaciers. Kuokuosele Glacier (G075156E38175N) showed a strong mass gain at its downstream part from 1973 to 1999, which, however, was limited to its continuously advancing tongue after 1999. Glacier G075075E38189N revealed down-wasting at its retreating tongue from 1973 to 1999, while surface elevation gain was observed in its middle part. This led to subsequent glacier advance with mass gain at its toe and loss in its middle part. Despite its more or less stable tongue was down-wasting observed for Kuosikulake (G075092E38214N) Glacier from 1973 to 1999. Following mass gain at its lower part might explain the sudden advance after 2009. Clear down-wasting despite stable frontal positions was observed for debris-covered Kekesayi (G075225E38255N) and G075171E38163N glaciers during the entire study time period.

Average mass budgets at Muztag Ata in the range of $-0.03 \pm 0.33\,\text{m w.e. a}^{-1}$ (1973–2009) to $-0.01 \pm 0.30\,\text{m w.e. a}^{-1}$ (1973–2013) are nearly balanced since more than 40 years. For different periods of the investigated time-span, however, mass changes strongly vary from one glacier to another. Kekesayi (G075225E38255N), as the largest glacier of the Muztag Ata Massif, shows ice mass loss during all investigated time periods. There are indications that most glaciers had more positive budgets in the last decade as compared to the period before 1999 (Tables 5). The time period between the ALOS-PRISM and Pléiades data takes is only four years and should be considered as too short for reliable results. Its difference image (Fig. ~~??~~7), however, shows mostly low noise, and ~~determined mass-balance~~

changes seem to fit with previous measurementsthe characteristics of surface elevation changes continue well in line with our results from other periods.

7.3 Glacier surface velocities of Kekesayi Glacier

Surface velocities of Kekesayi (G075225E38255N) Glacier reached up to 20 cm per day in August 2011 (Fig. 5). 2011. This corresponds to a maximal flow of $\sim$70 m per year when assuming if a similar flow throughout the year . would be assumed (Fig. 5). Ice flow at more than 15 cm per day ($\sim$55 m a^{-1}) is maximal at its middle part, downstream of the joining of the tributaries T2 and T3. Lateral surface movements, independent of the location, are slow due to retarding friction. Surface velocities slow down consistently with the glacier stream and become almost insignificant where stronger surface lowering occurs. Hence, we conclude that the glacier is stagnant as from about 3 km upstream of the terminus.

8 Discussion

8.1 Glacier area and length changes

Yao et al. (2012) found in the Eastern Pamir the least glacier shrinkage (-0.07 % a^{-1}) and retreat (-0.9 m a^{-1}) compared to the Tibetan Plateau and the Himalaya. More than 60 surging glaciers were identified for the time period from 1972 to 2006 in the central Pamir (Kotlyakov et al., 2008). This seems to be contrary to the observed high shrinkage Contrary to this trend was high shrinkage observed in the Zulumart Ranges south of Pamir Alay, where glaciers shrank -7.8 % (-0.65 % a^{-1}) from 1978 to 1990 and accelerated which accelerated to -11.6 % (-1.05 % a^{-1}) until 2001 (Khromova et al., 2006). Shrinkage was also measured reported by Shangguan et al. (2006) at the Muztag Ata and Kongur massifs and determined to be was measured to be at -7.9 % (-0.21 % a^{-1}) from 1962 to 1999. Area reduction went This was determined to come along with increasing retreat from -6.0 m a^{-1} (1962/1966–1990) to -11.2 m a^{-1} after 1990 (Shangguan et al., 2006). Our determined shrinkage of ($-$0.60.02 $\pm$ 3.90.1 % a^{-1}) and retreat (-1.0 ± 0.3 m a^{-1}) is much lower compared to several rates calculated per-glacier and to the aforementioned studies. We attribute such higher rates to the different sites and investigation periods of these studies. However, the differences can also stem from uncertain glacier boundaries in the Chinese Topographic maps (cf. Bolch et al., 2010) and as result of the more difficult glacier interpretation in Landsat imagery with a coarser resolution. In total, we would also expect less glacier shrinkage and retreat at Muztag Ata as in other areas of the Eastern Pamir study region of Yao et al. (2012) ~~subject to~~by reason of, on average, nearly balanced observed mass budgets in ~~these mountain massifs~~this study.

8.2 Glacier mass-balances

DEM differencing of multiple time periods confirms spatially as well as temporally inhomogeneous glacier mass changes at Muztag Ata, but on average nearly balanced budgets. These were determined to be -0.01 ± 0.30 to -0.03 ± 0.33 m w.e. a^{-1} from 1973 to 2009/2013 and to range from -0.04 ± 0.42 to $+0.04 \pm 0.27$ m w.e. a^{-1} for intermediate periods. Yao et al. (2012) measured a positive budget of $+0.25$ m w.e. a^{-1} from 2005/2006 to 2009/2010 by means of 13 measuring stakes for a small (size $\sim$1.1 km^2) west exposed glacier at Muztag Ata (38°14′ N, 75°03′ E, G075058E38248N). The net balance of this so called Muztag Ata Glacier No. 15 was positive in four of the five past observation years (Yao et al., 2012). Wide glacier coverage with positive Δh values in the difference image of 1999 to 2013 (Fig. 8) confirm these observations. Continued measurements based on additional observations above 5700 m a.s.l. with in total 19 stakes show less positive values of $+0.05$ m w.e. a^{-1} for 2010/2011 to 2013/2014. The after that reassessed values for the period from 2005/2006 until 2009/2010 reveal a positive value of $+0.16$ m w.e. a^{-1}. Measurements for the years 2001–2003 indicate almost balanced conditions at -0.01 m w.e. a^{-1} (unpublished data). Hence, the in-situ data is on average slightly lower but in tendency in good agreement with our geodetic estimations of $+0.21 \pm 0.27$ m w.e. a^{-1} for 1999–2013 ~~.~~ (Fig. 3).

Likely positive mass budgets of $+0.17 \pm 0.15$ m w.e. a^{-1} (Gardner et al., 2013) and of $+0.03 \pm 0.25$ m w.e. a^{-1} for the ablation area (Neckel et al., 2014) were also measured east of Muztag Ata in the western Kunlun Mountains by using ICESat laser altimetry data for the period of 2003–2009. The published data for the West Pamir vary: Gardner et al. (2013) and Kääb et al. (2015) determined likely negative mass budgets, based on the previously mentioned ICESat data, while Gardelle et al. (2013) found positive values of $+0.14 \pm 0.13$ m w.e. a^{-1} using SPOT and SRTM DEMs for the last decade. This deviation may be attributed to the uncertain penetration of SRTMs C-band radar into ice and snow.

An overall mass loss in the Western and Central Pamir seems to be more likely when considering the measured continuous glacier shrinkage (Khromova et al., 2006) as well as the negative mass budget of Abramov Glacier in Pamir Alay (measured years 1968–1997 and 2011/2012, WGMS, 2013) and the volume loss of Fedckenko Glacier, the by far largest and debris-covered glacier in the Central Pamir (Lambrecht et al., 2014). A region of positive anomaly seems to start in the Karakoram (Hewitt, 2005; Gardelle et al., 2012b) and continues over the Eastern Pamir (Yao et al., 2012; this study) to Western Kunlun (Gardner et al., 2013; Neckel et al., 2014; Kääb et al., 2015) and Central Tibet (Neckel et al., 2014).

8.3 Down-wasting, surface dynamics and area changes of debris-covered glaciers

Glacier tongues at Muztag Ata which reach below 4700 m a.s.l. are usually covered by debris, with increasing thicknesses of up to several meters at lower altitudes (Yang et al., 2013). Most of these glaciers do not show visual indications of retreat, and Shangguan et al. (2006) could not detect significant area changes at $\sim$90 glaciers at their Muztag Ata and Kongur study site, possibly due to debris cover. However, our results of DEM differencing exhibit clear surface lowering at the downstream glacier parts. This demonstrates that glaciers may have negative mass-balances despite thick debris cover and stable terminus positions. Decoupling of area from volume loss can be provoked by supraglacial debris, which can reduce glacier melt rates if debris coverage is exceeding a few centimeters of thickness. Stagnant debris-covered terminus positions must, hence, not indicate balanced glacier conditions (Bolch et al., 2011; Scherler et al., 2011; Lambrecht et al., 2014; Pellicciotti et al., 2015). In this regard, Fedchenko, as the Pamirs by far largest glacier, lost more than -5 km^3 of volume during the last eight decades (~ -6.0 %), but it shrank by only

−1.4 % at its debris-covered tongue (Lambrecht et al., 2014). Similar results were found by Pieczonka and Bolch (2015) for the Central Tien Shan.

The largest glacier at Muztag Ata, Kekesayi (G075225E38255N), appeared, by visual indication, to be stagnant from 1973 to 2013. DEM differencing, however, clearly indicates increasing ice mass loss at its downstream part during all investigated study periods. Surface lowering at the heavily debris-covered tongue reached up to 40 m in sum for the last four decadal measurements. Down-wasting becomes highest where surface velocities decrease to almost insignificant values, particularly about 3 km upward from its ~~toe~~terminus. A profile along the central glacier flow line supports an obvious relationship between surface velocity and down-wasting (Fig. 5). This was previously identified with similar methods by Pellicciotti et al. (2015) for debris-covered glaciers in the Central Himalaya. Yang et al. (2013) set a polynomial fit through multi-annual surface movements of Kekesayi Glacier, which were measured between 1998 and 2010 from Landsat imagery. The average upstream velocity of up to 50 m per year (∼ 14 cm per day) is in the range of our measurements~~.~~, while Zhou et al. (2014) presents winter velocities that did not exceed ∼ 11 m per year from 2008 to 2010. Glacier flow in 2009 shows lower rates in winter months (∼ 9 cm per day) as compared to summer rates at ∼ 15 cm per day (Yan et al., 2013a). These studies confirm seasonal and annual glacier flow variability at the central part of Kekesayi Glacier, with little or no fluctuations at the terminus. Its tongue is widely covered by supraglacial ponds that absorb large amounts of energy and thus contribute to down-wasting. The insulation effect of thick debris coverage, however, causes such glaciers to melt at lower rates, which might indicate retarded climate response. Down-wasting associated with negligible or little retreat in case of debris cover is also confirmed by studies of Bolch et al. (2008, 2011) and Pellicciotti et al. (2015). This underlines the importance of volume change investigations as more reliable indicators for climate-related glacier responses.

8.4 Glacier response to climate change

~~Seong et al. (2009a) found that glaciers at Muztag Ata have oscillated considerably throughout the Late Glacial and Holocene with at least 12 advances. During this time~~

~~the glaciation style has changed from an expanded ice cap to deeply entrenched valley and cirque glaciers. This is possibly reflected by responding to Northern Hemisphere climate and /or topographic constraints (Seong et al., 2009b, a).~~Both temperature and precipitation in this region has been increasing (Shi et al., 2007; Qiu, 2014). The summer temperature (June–August) at the close-by Taxkorgan meteorological station rose by $+0.7\,^{\circ}$C from 1957 and 2000 while annual precipitation slightly increased at the same time (Shangguan et al., 2006; Tian et al., 2006; Yao et al., 2012). In summer 2003, an ice core of 41.6 m in depth was drilled at 7010 m a.s.l. at Muztag Ata (38°17′ N, 75°06′ E, see Fig. 1) (Tian et al., 2006; Duan et al., 2007). Its isotope variations were found to be in good agreement with annual air temperature changes measured at Taxkorgan. However, starting in the 1990s, a more rapid warming trend of $+2.0$ to $+2.4\,^{\circ}$C per decade was observed, compared to Taxkorgan station measures at $+0.18\,^{\circ}$C per decade (Tian et al., 2006). Reconstructed mass balances rates do not agree with our results and show much higher wastage after 1990 (-0.42 m w.e. a^{-1}) as compared to the determined mean at -0.12 m w.e. a^{-1} for 1960 to 2003 (Duan et al., 2007).

Rising summer temperatures ~~measured since the 1990s might~~might, hence, have further accelerated glacier shrinkage, particularly since the 1990s (Khromova et al., 2006; Shangguan et al., 2006). Ablation is reported from June to August because of positive expected mean summer air-temperatures beyond the glacier terminus (Shangguan et al., 2006; Yang et al., 2013). It is, however, suggested that glaciers in this region are more sensitive to a change in precipitation as to temperature (cf. Seong et al., 2009a, b). ~~The mean annual precipitation to the glacier accumulation zone at Muztag Ata was measured to be ∼ 300 mm at 5910 m a.s.l. (38°42′ N, 75°01′ E). Summer precipitation is only accounting for 30 % of the annual total (Seong et al., 2009b, a).~~ Glaciers at Muztag Ata are situated at relatively high altitudes, where despite warming the air temperature still remains far below freezing during winter. Increasing precipitation from strengthening westerlies can, hence, lead to higher snow accumulation, which relatives the negative effects of climate change regarding warming. This might be one of the reasons why average shrinkage and ice mass loss at Muztag Ata is low and insignificant. Under current climate conditions, and by reason of increasing precipitation, would Yao et al. (2012) expect an advance of glaciers in the Eastern Pamir. The observed advance in this study might also be a response to three cooling periods with increasing annual precipitation measured from 1961–1968, 1973–1977 and 1985–1993 at Taxkogan Taxkorgan station (Shangguan et al., 2006).

8.5 Uncertainties of geodetic mass-balances from optical data

Low contrast alterations and over-saturation hampers terrain extraction from optical stereo-imagery, particularly at snow covered accumulation zones. Even the DEM of Substitution of low quality Δh values by zero in these zones is a consequence of lacking statistical alternatives. Potentially induced biases in volume change are therefore difficult to quantify and would be rather speculative. The impact is less critical for Pléiades is affected by large areas of poor or no elevation estimates, despite much as compared to ALOS-PRISM (2.5 m, 8-bits), since its higher geometric (0.5 m) and radiometric (12-bits) resolution in comparison to ALOS-PRISM (2.5 m, 8-bits) or led to a lower rate of of poor elevation estimates. KH-9 Hexagon (6–9 m, 8-bits). Gap-filling by zero in glacier accumulation zones is a consequence of lacking statistical alternatives, but might induce biased estimates in volume change. KH-9 Hexagon , moreover, shows high noise at low-contrast terrain in its DEM , but much better results at debris-covered at low-contrast terrain. Debris-covered and crevassed glacier surfaces. , however, are of much better quality, and to that effect its relatively high NMAD is possibly overestimated. Multi-temporal results proof to be in line despite of such uncertainties and median values close to zero (the mean is by construction zero) give confidence of a safe, almost gaussian distribution (Table 2). The vertical precision in this study is in the range of the SRTM-3 accuracy specifications. These are stated to be ±6 m relative and ±16 m absolute (Rabus et al., 2003). Calculated difference images and determined mass-balances of multiple time periods are in line with each other. Median values that are close to zero (the mean is by construction zero) give confidence of a safe, almost gaussian distribution (Table 2). We would expect a higher precision in case of a more accurate reference than the SRTM-3 DEM. This assumption is supported by similar NMAD values from optical stereo data in the study of Pieczonka et al. (2013), and by a much lower

NMAD of 2.5 m from high-resolution DEM differencing of ALOS-PRISM to Pléiades in this study (Fig. ~~??~~7).

8.6 SRTM C-band penetration depth correction

Specific C-band penetrations into snow and ice must be corrected for SRTM due to different weather and the subsequent snow-cover conditions during the acquisition in February 2000. This is particularly important for winter accumulation type glaciers, as it is the case at Muztag Ata. The C-band radar waves penetrate into clean glacier ice and particularly through newly fallen layers of fresh snow. Penetrations reach up to 10 m in dry cold firn and 2 m in exposed ice (Rignot et al., 2001). Gardelle et al. (2013) measured mean penetrations of 1.8 ± 1.5 m in glaciers of the Pamir, but admits that this value might be underestimated. This is supported by Kääb et al. (2015) who found larger SRTM C-band penetrations of 5–6 m in the Pamir. We therefore referred to larger estimates which were determined for the three nearby Hindu-Kush, Karakoram and Jammu-Kashmir study sites of Kääb et al. (2012). Its westerly influenced glaciers are situated more south but at about the same latitude, and we, hence, suppose similar penetrations for Muztag Ata despite a higher degree of continentality. Penetration depths in these regions are 5.1 ± 0.7 m, 5.5 ± 0.3 m and 2.3 ± 0.9 m for firn and snow, as well as 1.7 ± 0.6 m, 1.1 ± 0.5 m and 1.7 ± 0.7 m for clean ice respectively (Kääb et al., 2012). We averaged these estimates in consideration of their wide geographic spreading. Slightly negative mass budgets observed from 1973 to 1999, compared to more positive values after 1999, might still indicate underestimated corrections. ~~Eventually~~ Possibly biased trends prior and after 1999 are, however, insignificantly low and the derived mass-balance results are well in line. DEM differencing solely based on optical data is not subject to such eventual biases. There was no need for seasonal corrections, since imagery for DEM extraction was acquired during summer months when snow accumulation was negligible.

9 Conclusions

Glaciers at Muztag Ata, situated in the Eastern Pamir, are of high importance for seasonal freshwater supply and act as valuable climate indicator. Detailed knowledge of glacier changes in this remote and high mountain region is, however, scarce. We used remote sensing datasets of Hexagon KH-9 (1973), ALOS-PRISM (2009), Pléiades (2013) and Landsat 7 ETM+ in conjunction with SRTM-3 (2000) to investigate four decades of glacier variations at Muztag Ata. These are heterogeneous and differ spatially as well as temporally. ~~Numerous mostly~~ The debris-covered glaciers show no or only negligible visual changes at their frontal position. Differencing of multi-temporal Digital Elevation Models (DEMs), however, reveals clear down-wasting at their tongues, despite mostly thick debris coverage. Some south-west exposed glacier tongues fluctuated or advanced, with infrequent variations in ice thickness. The total glacier shrinkage of $-0.02 \pm 0.1\,\%\,\mathrm{a}^{-1}$, from $274.3 \pm 10.6\,\mathrm{km}^2$ in 1973 to $272.7 \pm 1.0\,\mathrm{km}^2$ in 2013, is low and not significant. Averaged mass budgets based on geodetic measurements are slightly but insignificantly negative before 1999 ($-0.04 \pm 0.42\,\mathrm{m\,w.e.\,a}^{-1}$) and positive afterwards ($+0.04 \pm 0.27\,\mathrm{m\,w.e.\,a}^{-1}$). This might still result from ~~an eventually~~ a potentially underestimated SRTM-3 C-band penetration into snow and ice. Slightly positive observed budgets after 1999~~are~~, however, ~~more likely a response to strengthening westerlies~~ could possibly reflect a regional-wide positive anomaly with increasing snow accumulation from strengthening westerlies. Mass gain for glacier G075058E38248N (so called Muztag Ata Glacier No. 15) is confirmed by in-situ measurements for the period 2001–2014. Differencing based on only optical DEMs is not subject to penetration depth uncertainties. Optical approaches indicate nearly balanced budgets for the last four decades (-0.01 ± 0.30 to $-0.03 \pm 0.33\,\mathrm{m\,w.e.\,a}^{-1}$). Kekesayi (G075225E38255N) as the largest glacier at Muztag Ata shows more negative trends in the range of -0.08 ± 0.30 to $-0.11 \pm 0.33\,\mathrm{m\,w.e.\,a}^{-1}$ from 1973 to 2009/2013. Amplitude tracking of TerraSAR-X data from summer 2011 indicates a stagnant glacier tongue where down-wasting occurs. Upstream velocities fluctuate in its tributaries and are in the range of $\sim$10–15 cm per day.

Our study emphasizes the importance of volume change investigations, particularly for debris-covered glaciers. Largely untouched stereo photographs of the US Keyhole-9 spy program provide long-term information of historic glacier situations and were highly valuable for volume change investigations prior to the acquisition date of SRTM. ~~In~~ This study presents, in combination with the recently recorded high-resolution Pléiades imagery~~presents this study ,~~, the longest time series of geodetic mass-balances for the Eastern Pamir at the glacier scale.

Author contributions. T. Bolch, M. Buchroithner and N. Holzer designed the study. N. Holzer processed all data from optical sensors (Hexagon KH-9, ALOS-PRISM, Pléiades, Landsat 7 ETM+) and SRTM-3, determined changes in glacier length and area, and performed geodetic mass balances. S. Vijay presented surface velocities of Kekesayi Glacier which he calculated by SAR-processing (TerraSAR-X). T. Yao and B. Xu provided the updated in-situ mass budget data of Muztag Ata Glacier No. 15 as well as comments to this study. N. Holzer and S. Vijay wrote the manuscript, all authors contributed to the final form of this article.

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Table 1. Overview of optical stereo imagery used for DEM extraction and subsequent geodetic mass-balance measurements.

Optical sensor (stereo)	Acquisition date	Stereo mode (b/h-ratio)	Spatial/radiometric res.
Pléiades HR 1B	19 Jun 2013	Standard (0.28)	0.5 m (pan)/12-bits
Pléiades HR 1A	20 Jun 2013	Standard (0.20)	0.5 m (pan)/12-bits
Pléiades HR 1B	3 Aug 2013	Standard (0.29)	0.5 m (pan)/12-bits
ALOS-PRISM	10 Sep 2009	Tri-stereo (0.50)	2.5 m/8-bits
Hexagon KH-9	4 Aug 1973	Tri-stereo (0.40)	6–9 m/8-bits

Table 2. Vertical uncertainties of DEM differencing on stable terrain with KH-9 Hexagon (1973), SRTM-3 (1999), ALOS-PRISM (2009) and Pléiades (2013).

Δh time period	NMAD [m]	Median [m]	68.3 % quantile [m]	95 % quantile [m]	STD [m]
2009–2013	2.50	−0.04	2.53	4.71	2.41
1999–2013	4.43	−0.05	4.61	8.71	4.43
1999–2009	5.17	−0.02	5.36	10.09	5.14
1973–2013	14.08	−0.22	14.23	25.97	13.45
1973–2009	13.88	−0.22	14.05	25.79	13.31
1973–1999	12.80	−0.23	12.95	23.50	12.20

The mean equals to zero (RMSE = STD).

Table 3. Glacier length changes (ΔL) at Muztag Ata for selected glaciers that have mass-balance estimates.

Glacier (GLIMS ID)	$\Delta L_{1973-2000}$ [m]	$\Delta L_{2000-2009}$ [m]	$\Delta L_{2009-2013}$ [m]	$\Delta L_{1973-2013}$ [m]
G075225E38255N (Kekesayi)	0.0 ± 12.5	0.0 ± 7.8	0.0 ± 2.2	0.0 ± 10.0
G075233E38272N	-30.0 ± 12.5	-180.0 ± 7.8	-40.0 ± 2.2	-250.0 ± 10.0
G075175E38297N	-380.0 ± 12.5	-40.0 ± 7.8	$+20.0 \pm 2.2$	-400.0 ± 10.0
G075101E38308N	0.0 ± 12.5	0.0 ± 7.8	0.0 ± 2.2	0.0 ± 10.0
G075079E38288N (Kematulejia)	-190.0 ± 12.5	0.0 ± 7.8	0.0 ± 2.2	-190.0 ± 10.0
G075084E38279N	-60.0 ± 12.5	0.0 ± 7.8	0.0 ± 2.2	-60.0 ± 10.0
G075077E38257N (Kalaxiong)	0.0 ± 12.5	0.0 ± 7.8	0.0 ± 2.2	0.0 ± 10.0
G075058E38248N (Muztag Ata)	0.0 ± 12.5	0.0 ± 7.8	0.0 ± 2.2	0.0 ± 10.0
G075071E38240N	-110.0 ± 12.5	-40.0 ± 7.8	0.0 ± 2.2	-150.0 ± 10.0
G075092E38214N (Kuosikulake)	0.0 ± 12.5	-350.0 ± 7.8	$+250.0 \pm 2.2$	-100.0 ± 10.0
G075075E38189N	-150.0 ± 12.5	$+130.0 \pm 7.8$	$+50.0 \pm 2.2$	$+30.0 \pm 10.0$
G075156E38175N (Kuokuosele)	$+150.0 \pm 12.5$	$+340.0 \pm 7.8$	$+130.0 \pm 2.2$	$+620.0 \pm 10.0$
G075171E38163N	0.0 ± 12.5	0.0 ± 7.8	0.0 ± 2.2	0.0 ± 10.0
Selected glaciers ($\bar{X}$)	-59.2 ± 12.5	-10.8 ± 7.8	$+31.5 \pm 2.2$	-38.5 ± 10.0
Selected glaciers ($\bar{X}$) per year	-2.2 ± 0.5	-1.2 ± 0.9	$+7.9 \pm 0.6$	-1.0 ± 0.3

Table 4. Equilibrium Line Altitude (ELA), Glacier area (A) and changes (ΔA) from 1973–2013 at Muztag Ata for selected glaciers that have mass-balance estimates and for all glaciers of the study site.

Glacier (GLIMS ID)	ELA [m]	A_{1973} [km^2]	A_{2000} [km^2]	A_{2009} [km^2]	A_{2013} [km^2]	$\Delta A_{1973-2013}$ [km^2]
G075225E38255N (Kekesayi)	4900	54.5 ± 1.13	54.5 ± 0.85	54.5 ± 0.23	54.5 ± 0.11	0.0 ± 1.1 (0.0 ± 2.1 %)
G075233E38272N	4770	9.4 ± 0.26	9.2 ± 0.20	9.2 ± 0.06	9.2 ± 0.03	-0.2 ± 0.3 (-2.7 ± 2.8 %)
G075175E38297N	4820	6.6 ± 0.18	6.5 ± 0.13	6.5 ± 0.03	6.5 ± 0.02	-0.1 ± 0.2 (-2.3 ± 2.7 %)
G075101E38308N	4970	7.3 ± 0.21	7.3 ± 0.16	7.3 ± 0.04	7.3 ± 0.02	0.0 ± 0.2 (0.0 ± 2.9 %)
G075079E38288N (Kematulejia)	5940	8.5 ± 0.22	8.4 ± 0.17	8.4 ± 0.04	8.4 ± 0.02	-0.1 ± 0.2 (-0.7 ± 2.6 %)
G075084E38279N	5940	11.1 ± 0.25	11.1 ± 0.19	11.1 ± 0.05	11.1 ± 0.02	0.0 ± 0.2 (0.0 ± 2.2 %)
G075077E38257N (Kalaxiong)	5460	15.4 ± 0.43	15.4 ± 0.32	15.4 ± 0.09	15.4 ± 0.04	0.0 ± 0.4 (0.0 ± 2.8 %)
G075058E38248N (Muztag Ata)	5470	0.9 ± 0.06	0.9 ± 0.04	0.9 ± 0.01	0.9 ± 0.01	0.0 ± 0.1 (0.0 ± 6.2 %)
G075071E38240N	5460	8.2 ± 0.23	8.1 ± 0.17	8.1 ± 0.05	8.1 ± 0.02	-0.1 ± 0.2 (-1.4 ± 2.8 %)
G075092E38214N (Kuosikulake)	5410	12.8 ± 0.33	12.8 ± 0.25	12.6 ± 0.06	12.7 ± 0.03	-0.1 ± 0.3 (-0.6 ± 2.6 %)
G075075E38189N	5410	2.6 ± 0.15	2.5 ± 0.11	2.7 ± 0.03	2.7 ± 0.02	$+0.1 \pm 0.2$ ($+3.0 \pm 5.9$ %)
G075156E38175N (Kuokuosele)	5190	16.2 ± 0.42	16.4 ± 0.31	16.5 ± 0.09	16.6 ± 0.04	$+0.4 \pm 0.4$ ($+2.1 \pm 2.6$ %)
G075171E38163N	5110	5.8 ± 0.24	5.8 ± 0.18	5.8 ± 0.05	5.8 ± 0.02	0.0 ± 0.2 (0.0 ± 4.1 %)
Selected glaciers ($\sum$)	5296	159.5 ± 4.1	159.0 ± 3.1	159.0 ± 0.8	159.2 ± 0.4	-0.3 ± 4.1 (-0.2 ± 2.6 %)
All glaciers study site	5285	274.3 ± 10.6	272.7 ± 7.9	272.5 ± 2.1	272.7 ± 1.0	-1.6 ± 10.6 (-0.6 ± 3.9 %)

ELAs adapted from the first Chinese Glacier Inventory (cf. Shi et al., 2008)

~~Glacier mean elevation (Δh) and total ice volume changes, as well as glacier mass-balance rates measured from DEM differencing of KH-9 Hexagon (1973), SRTM-3 (1999), ALOS-PRISM (2009) and Pléiades (2013).~~

Table 5. Glacier mean elevation (Δh) and total ice volume changes, as well as geodetic glacier mass-balance rates measured from DEM differencing of KH-9 Hexagon (1973), SRTM-3 (1999), ALOS-PRISM (2009) and Pléiades (2013).

Glacier (GLIMS ID)	1973–2013	1973–2009	1973–1999	1999–2013	1999–2009	2009–2013
G075225E38255N (Kekesayi)						
Mean Δh [m]	-3.97 ± 14.08	-4.52 ± 13.88	-3.42 ± 12.83	-0.69 ± 4.52	-0.55 ± 5.25	-0.76 ± 2.50
Volume change [Gt $\times 10^{-3}$]	-183.8 ± 652.4	-209.4 ± 643.2	-158.5 ± 594.9	-31.9 ± 209.4	-25.3 ± 243.4	-35.3 ± 116.0
Annual mass-balance [m w.e. a^{-1}]	-0.08 ± 0.30	-0.11 ± 0.33	-0.11 ± 0.42	-0.04 ± 0.27	-0.05 ± 0.45	-0.16 ± 0.53
G075233E38272N						
Mean Δh [m]	-1.40 ± 14.08	-3.21 ± 13.88	-1.51 ± 12.83	-0.01 ± 4.52	-0.95 ± 5.25	-0.10 ± 2.50
Volume change [Gt $\times 10^{-3}$]	-11.2 ± 112.5	-25.6 ± 110.9	-12.0 ± 102.5	-0.1 ± 35.4	-7.4 ± 41.2	-0.8 ± 19.5
Annual mass-balance [m w.e. a^{-1}]	-0.03 ± 0.30	-0.08 ± 0.33	-0.05 ± 0.42	0.0 ± 0.27	-0.08 ± 0.45	-0.02 ± 0.53
G075175E38297N						
Mean Δh [m]	-1.91 ± 14.08	-3.59 ± 13.88	-4.73 ± 12.83	$+2.91 \pm 4.52$	$+1.77 \pm 5.25$	$+0.95 \pm 2.50$
Volume change [Gt $\times 10^{-3}$]	-10.8 ± 79.5	-20.3 ± 78.4	-26.7 ± 72.5	$+16.1 \pm 25.0$	$+9.8 \pm 29.1$	$+5.3 \pm 13.9$
Annual mass-balance [m w.e. a^{-1}]	-0.04 ± 0.30	-0.08 ± 0.33	-0.15 ± 0.42	$+0.18 \pm 0.27$	$+0.15 \pm 0.45$	$+0.20 \pm 0.53$
G075101E38308N						
Mean Δh [m]	-2.07 ± 14.08		-3.29 ± 12.83	$+1.32 \pm 4.52$		
Volume change [Gt $\times 10^{-3}$]	-12.9 ± 87.9		-20.5 ± 80.2	$+8.2 \pm 28.2$		
Annual mass$-$balance [m w.e. a^{-1}]	-0.04 ± 0.30		-0.11 ± 0.42	$+0.08 \pm 0.27$		
G075079E38288N (Kematulejia)						
Mean Δh [m]	-1.09 ± 14.08		-1.53 ± 12.83	$+0.94 \pm 4.52$		
Volume change [Gt $\times 10^{-3}$]	-7.9 ± 102.0		-11.1 ± 93.0	$+6.8 \pm 32.5$		
Annual mass-balance [m w.e. a^{-1}]	-0.02 ± 0.30		-0.05 ± 0.42	$+0.06 \pm 0.27$		
G075084E38279N						
Mean Δh [m]				$+2.76 \pm 4.52$	$+2.47 \pm 5.25$	
Volume change [Gt $\times 10^{-3}$]				$+25.9 \pm 42.5$	$+23.2 \pm 49.4$	
Annual mass-balance [m w.e. a^{-1}]				$+0.17 \pm 0.27$	$+0.21 \pm 0.45$	
G075077E38257N (Kalaxiong)						
Mean Δh [m]	-0.70 ± 14.08		-1.25 ± 12.83	$+0.67 \pm 4.52$		
Volume change [Gt $\times 10^{-3}$]	-9.2 ± 184.2		-16.4 ± 168.0	$+8.7 \pm 59.1$		
Annual mass$-$balance [m w.e. a^{-1}]	-0.01 ± 0.30		-0.04 ± 0.42	$+0.04 \pm 0.27$		

Table 5. Continued.

Glacier (GLIMS ID)	1973–2013	1973–2009	1973–1999	1999–2013	1999–2009	2009–2013
G075058E38248N (Muztag Ata)						
Mean Δh [m]				$+3.49 \pm 4.52$		
Volume change [Gt $\times 10^{-3}$]				$+2.8 \pm 3.6$		
Annual mass-balance [m w.e. a^{-1}]				$+0.21 \pm 0.27$		
G075071E38240N						
Mean Δh [m]				$+2.23 \pm 4.52$		
Volume change [Gt $\times 10^{-3}$]				$+15.4 \pm 31.3$		
Annual mass-balance [m w.e. a^{-1}]				$+0.14 \pm 0.27$		
G075092E38214N (Kuosikulake)						
Mean Δh [m]		$+0.61 \pm 13.88$	$+0.15 \pm 12.83$		$+1.38 \pm 5.25$	
Volume change [Gt $\times 10^{-3}$]		$+6.6 \pm 150.9$	$+1.6 \pm 139.6$		$+15.0 \pm 56.9$	
Annual mass-balance [m w.e. a^{-1}]		$+0.01 \pm 0.33$	0.0 ± 0.42		$+0.12 \pm 0.45$	
G075075E38189N						
Mean Δh [m]	$+0.41 \pm 14.08$	$+0.35 \pm 13.88$	$+0.5 \pm 12.83$	$+0.43 \pm 4.52$	$+0.66 \pm 5.25$	$+0.17 \pm 2.50$
Volume change [Gt $\times 10^{-3}$]	$+0.9 \pm 32.0$	$+0.8 \pm 31.4$	$+1.1 \pm 28.4$	$+1.0 \pm 10.3$	$+1.5 \pm 11.9$	$+0.4 \pm 5.7$
Annual mass-balance [m w.e. a^{-1}]	$+0.01 \pm 0.30$	$+0.01 \pm 0.33$	$+0.02 \pm 0.42$	$+0.03 \pm 0.27$	$+0.06 \pm 0.45$	$+0.04 \pm 0.53$
G075156E38175N (Kuokuosele)						
Mean Δh [m]	$+3.48 \pm 14.08$	$+2.81 \pm 13.88$	$+2.75 \pm 12.83$	$+1.25 \pm 4.52$	$+0.58 \pm 5.25$	$+0.34 \pm 2.50$
Volume change [Gt $\times 10^{-3}$]	$+49.0 \pm 198.4$	$+39.4 \pm 194.8$	$+38.3 \pm 178.6$	$+17.6 \pm 63.7$	$+8.1 \pm 73.7$	$+4.8 \pm 35.3$
Annual mass$-$balance [m w.e. a^{-1}]	$+0.07 \pm 0.30$	$+0.07 \pm 0.33$	$+0.09 \pm 0.42$	$+0.08 \pm 0.27$	$+0.05 \pm 0.45$	$+0.07 \pm 0.53$
G075171E38163N						
Mean Δh [m]	-4.15 ± 14.08	-3.70 ± 13.88	-1.58 ± 12.83	-2.59 ± 4.52	-1.19 ± 5.25	-0.90 ± 2.50
Volume change [Gt $\times 10^{-3}$]	-20.4 ± 69.1	-18.1 ± 68.1	-7.7 ± 63.0	-12.7 ± 22.2	-5.8 ± 25.8	-4.4 ± 12.3
Annual mass-balance [m w.e. a^{-1}]	-0.09 ± 0.30	-0.09 ± 0.33	-0.05 ± 0.42	-0.16 ± 0.27	-0.10 ± 0.45	-0.19 ± 0.53
All glaciers study site						
Mean Δh [m]	-0.62 ± 14.08	-1.24 ± 13.88	-1.32 ± 12.83	$+0.62 \pm 4.52$	$+0.44 \pm 5.25$	-0.31 ± 2.50
Volume change [Gt $\times 10^{-3}$]	-146 ± 3288	-290 ± 3240	-308 ± 2993	$+145 \pm 1049$	$+103 \pm 1217$	-72 ± 580
Annual mass$-$balance [m w.e. a^{-1}]	-0.01 ± 0.30	-0.03 ± 0.33	-0.04 ± 0.42	$+0.04 \pm 0.27$	$+0.04 \pm 0.45$	-0.07 ± 0.53

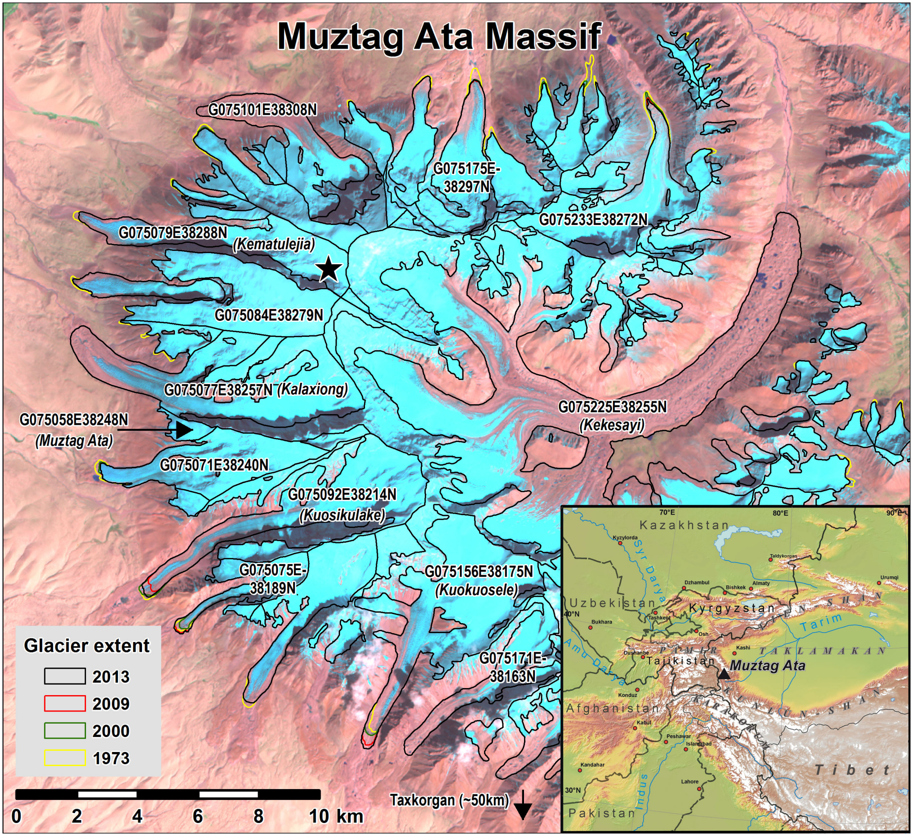

Figure 1. Overview of the Muztag Ata study site with investigated glaciers according to their ID in GLIMS (background image: Landsat 7 ETM+ of 11 September 2000; *: ice core location (cf. Tian et al., 2006; Duan et al., 2007)).

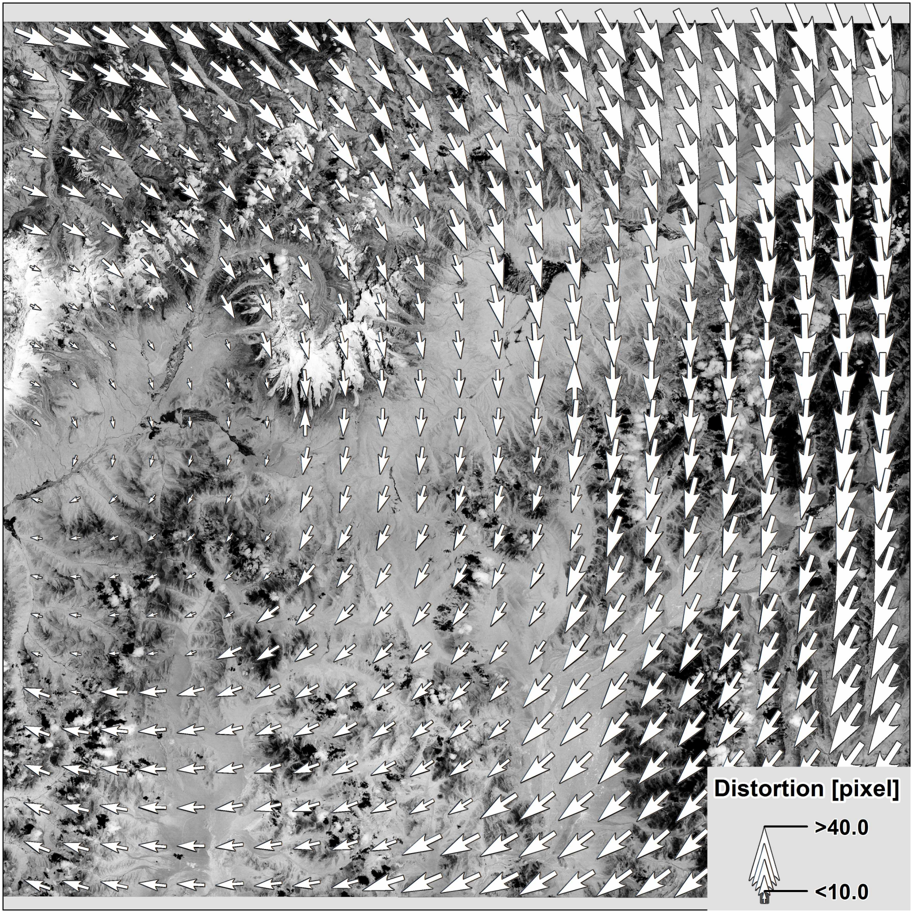

Figure 2. Distortion vectors of reseau-crosses from their measured to their initial reference positions in a KH-9 photograph segment covering Muztag Ata (frame 17a of mission 1206-5).

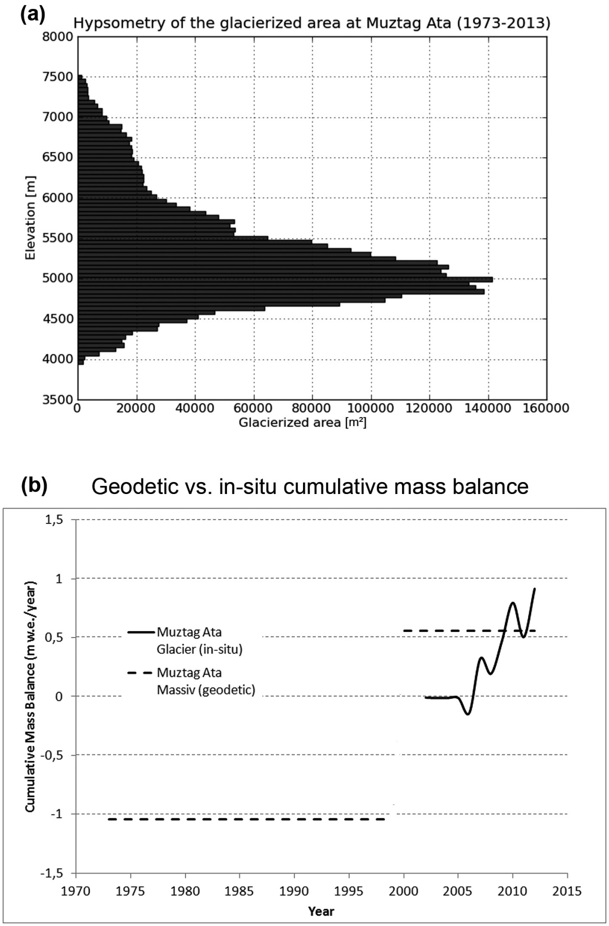

Figure 3. (a) Hypsometry of the glacierized area at Muztag Ata, **(b)** cumulative vs. in-situ measured mass balance for Muztag Ata Glacier (G075058E38248N) and the entire massif.

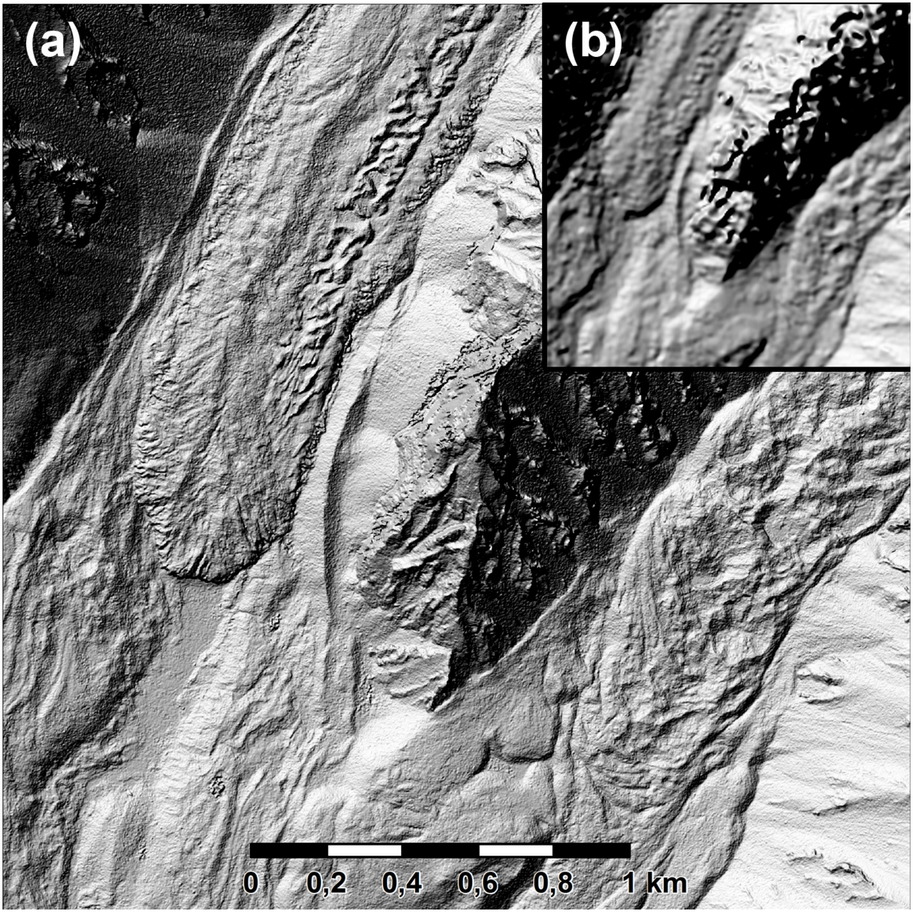
(a)
(b)
0
0,2
0,4
0,6
0,8
1 km

Figure 4. **(a)** Hillshade of the Pléiades DEM at 1 m resolution with advancing tongue of Kuokuosele Glacier (G075156E38175N, left) and stable tongue of glacier G075171E38163N (as right), **(b)** compared to 10 m DEM of ALOS-PRISMat the upper right). **(b)** Distortion vectors of reseau-crosses from their measured to their initial reference positions in a KH-9 photograph segment covering Muztag Ata (frame 17a of mission 1206-5).

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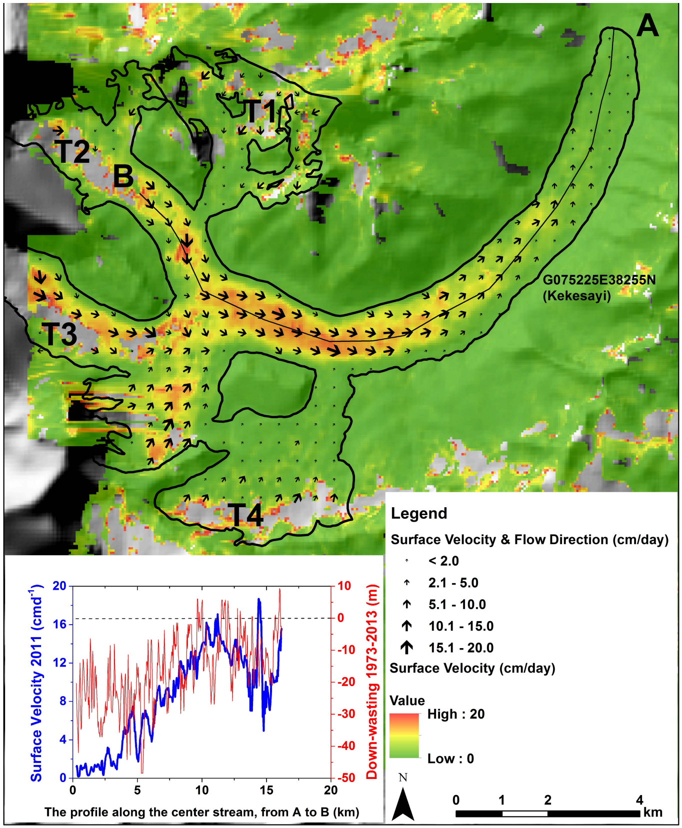
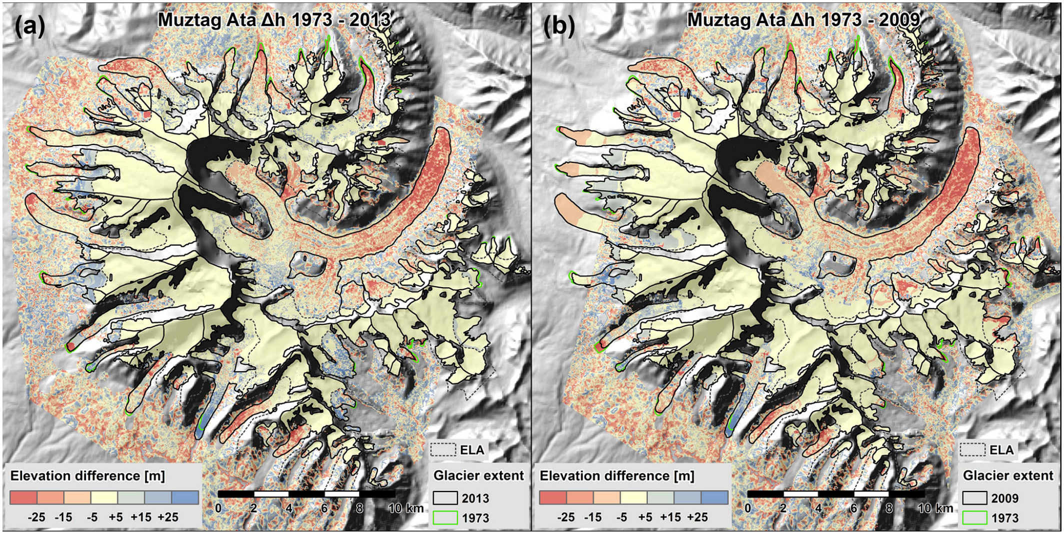


Figure 5. Surface velocities and flow directions of Kekesayi (G075225E38255N) Glacier in August 2011. The profile shows the surface velocities and the corresponding down-wasting (1973–2013) along the central glacier flow line, upstream from A to B.



~~Co-registered difference images of~~ 1973–2013 **(a)** and 1973–2009 **(b)** after outlier and gap-filling processing for glacier mass-balance and vertical uncertainty calculation (ELA adapted from Shi et al. (2008)).

~~Co-registered difference images of~~ 1973–2013 **(a)** and 1973–2009 **(b)** after outlier and gap-filling processing for glacier mass-balance and vertical uncertainty calculation (ELA adapted from Shi et al. (2008)).

Figure 6. Co-registered difference images of ~~1999–2013 **(a)** and 1999–2009 **(b)** after outlier and gap-filling processing for glacier mass-balance and vertical uncertainty calculation.~~
~~Co-registered difference images of~~ 1973–2013 **(a)** and 1973–2009 **(b)** after outlier and gap-filling processing for glacier mass-balance and vertical uncertainty calculation (ELA adapted from Shi et al. (2008)).

Co-registered difference images of 2009–2013 **(a)** and 1973–1999 **(b)** after outlier and gap-filling processing for glacier mass-balance and vertical uncertainty calculation.

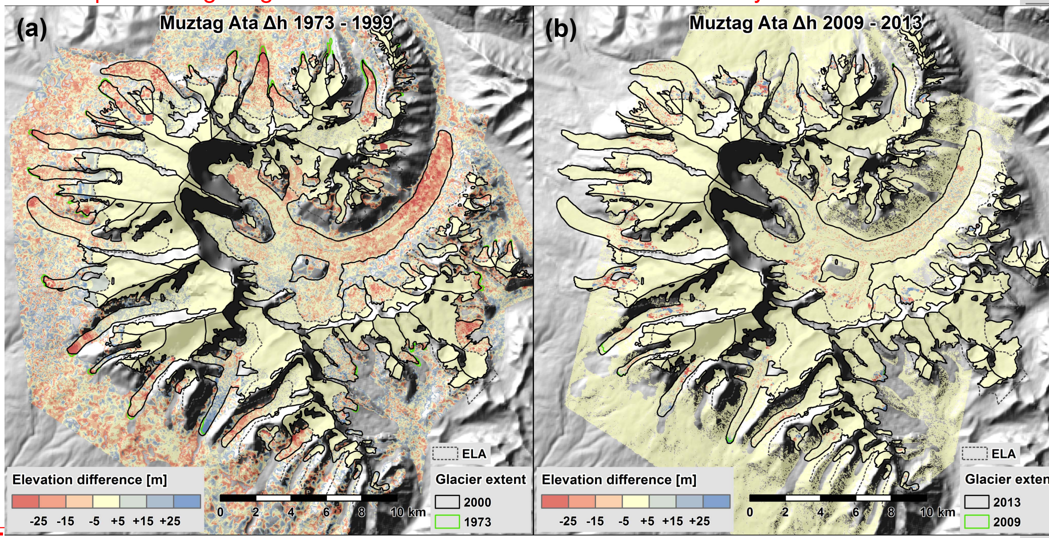


Figure 7. Co-registered difference images of 1973–1999 **(a)** and 2009–2013 **(b)** after outlier and gap-filling processing for glacier mass-balance and vertical uncertainty calculation (ELA adapted from Shi et al. (2008)).

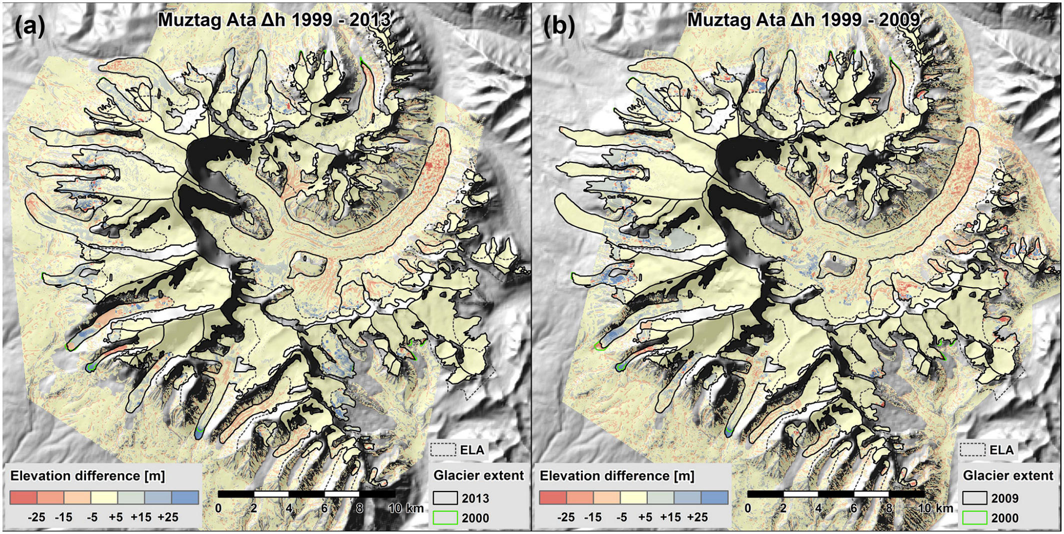


Figure 8. Co-registered difference images of 1999–2013 **(a)** and 1999–2009 **(b)** after outlier and gap-filling processing for glacier mass-balance and vertical uncertainty calculation (ELA adapted from Shi et al. (2008)).