Point-by-point reply to editor comments

Editor review (21 Sep 2015) by Etienne Berthier

Journal: TC
Title: Four decades of glacier variations at Muztag Ata (Eastern Pamir): a multi-sensor study including Hexagon KH-9 and Pléiades data
Author(s): N. Holzer et al.
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Dear Nicolai Holzer and Tobias Bolch,

I have now read your revised manuscript and your response to the referees. Both referees were rather positive about your study although they made numerous suggestions to improve the manuscript, in particular its structure.

You addressed satisfyingly most of their comments.

However, I still have myself some comments on your paper. You will find them in the attached annotated document. Feel free to contact me directly if something is unclear. I believe that the language could still be improved (I am not the best person to correct it), at least to avoid any ambiguity.

To facilitate and speed up the review process, please attach to your revised manuscript a cover letter detailing the changes you have made in response to my comments.

Good luck with the second round of revision,

Etienne Berthier

Dear Etienne,

Thank you for your helpful and valuable comments to improve the quality of our publication. Please find below our point-to-point cover letter regarding our responses to your comments and recommendations, as well as the employed changes in the manuscript.

Kind regards

Nicolai Holzer and co-authors

Comments

Abstract (P2):

L2:field? glaciological? to clarify the contrast with your new measurements?.

Reply: "*Previous measurements in the Eastern Pamir*" refer to the study of Yao et al. (2012) who measured a positive mass balance of +0.25mw.e. a^{-1} for so called Muztag Ata Glacier No. 15 in the field. Our study extends theses measurements "in space and time" by using remote sensing data. We changed the sentence accordingly to "*Previous in-situ measurements indicated a slight mass gain …*". We omitted the words "*mass balance*" due to the later "*mass gain*".

L10: unclear. Rather: "amplitude tracking of TerraSAR-X images acquired in 2011" or somthing similar.

Reply: Changed to *"…were derived from amplitude tracking of TerraSAR-X images (2011)*." We prefer "(2011)" instead of "*acquired in 2011*", similarly as mentioned for other datasets, by trying to keep the abstract short.

L15-16: what about "of this debris-covered glacier, the largest of the massif,"

Reply: We changed the sentence, but we did not keep "*…,the largest of the massif,…*". We remarked that this information is already provided in the abstract at line 9 before ("*…,the largest glacier at Muztag Ata,…*").

L15-16: "distal" is not really usual (at least a bit unclear to me). "lowest part"?

Reply: Changed according to your suggestion to "*…the lowest part of the tongue…*"

L22: it is not a trend. Rather "indications of slightly positive (but not signicant) mass-balance rates after 1999..."?

Reply: OK we agree, we changed this sentence to "*Indications of slightly positive rates after 1999 (+0.04±0.27mw.e. a^{-1}) are not significant, but confirmed by measurements in the field."*

1 Introduction

Page 3

L13-24: I am not really convinced by this paragraph. Not sure it should be retained in the introduction. Climate is already presented in the Study Area section and then in the discussion. After removal, the introduction would be shorten and more "to the point"

Reply: We agree that climate is already presented in the study area section, but we still consider this paragraph as important. We now associated the study area section to the introduction and merged this paragraph with the climate section. The introduction was subsequently modified and improved. The paragraph citing Zhang et al (2012), a paragraph citing Yao et al. (2012) and a shortened paragraph citing Seong et al. (2009a,b) was moved to the more appropriate section "*Glacier response to climate change*". The paragraph of Yao et al. (2012) about "*Warming was most observed at altitudes between 4800m and 6200ma.s.l. …*" was deleted. By this means, the introduction combined with the study area could be shortened.

L17: wording not appropriate. "mainly" maybe? Do you want to state that the warming has been the greatest in this elevation band? I was unsure.

Reply: Yes, we want to state that warming has been the greatest in this elevation band (Yao et al. (2012): "*The rate of warming is highest between 4,800 and 6,200m above sea level (a.s.l.)*"). Changed according to your suggestion.

L17: add "," here

Reply: Changed according to your suggestion

Page 4

L1: Wording unclear. What do you mean?

Reply: We agree that the wording of this sentence is unclear. We decided to omit the entire sentence "*This is possibly reflected by responding to Northern Hemisphere climate and/or topographic constraints*" as citation of Seong et al. (2009b, a) since it would require further explanation that is not important at this point (introduction)

L17: gradients of what? Climate? Morphological?

Reply: Gradients in terms of topography. We replaced "*higher gradients*" with "*steeper slopes*".

L19: move between "Glacier" and "by" (I think)
Reply: Changed according to your suggestion

Page 5

L2-L3: I suggest "the mean annual precipitation at 5910 m asl, in the accumulation zone of Muztag Ata glacier, was measured..
Reply: This information is cited from Seong et al. (2009a,b), e.g.: "*At Muztag Ata (Fig.1; 38 42' N, 75°01' E, 5910masl), the precipitation supplied to the glacier accumulation zone during the summer is <30% of total annual amount (300 mm/yr at 5910masl).*" We entirely re-organized and shortened this sentence to the following" *Summer precipitation at the glacier accumulation zone at Muztag Ata is estimated to only account for 30% of the total annual amount, which was measured to be ~300mm at 5910ma.s.l. (38°42' N, 75°01' E) (Seong et al., 2009b, a)*."

L23: "from"?
Reply: Changed according to your suggestion

Page 6

L1: could you double check this? I am surprised. French and Italy had a joint agreement (Orfeo) with the French in charge of the optical part (Pléiades) and Italy of the radar part (Cosmo Skymed) but I do not think Italy was involved in the design of the Pléiades satellites. To be verified. If true, I would state "by the French Space Agency (CNES)"
Reply: You are right. We shortened this section during revision as suggested by the reviewers, but in this constellation the provided information is no more correct. The sentence in TCD was initially as follows: "*Pléiades is an optical high resolution earth observation satellite system developed as part of the intergovernmental ORFEO agreement between France and Italy*." We changed phrasing of this sentence and corrected it accordingly to "*Pléiades is a high resolution satellite system developed by France*".

L23: is it the "location accuracy"? Unclear to me what is the "geometric accuracy"
Reply: The term "*location accuracy*" is found in several documentations about ALOS PRISM, particularly Tadono et al. (2009): "*For absolute geometric accuracies, we achieved 8.1 m for nadir-looking images and 9.3 m for forward- and backward-looking images of PRISM*". Since this refers to "*location accuracy*", it was replaced in the manuscript.

L26: rather "was provided with"
Reply: We modified the sentence and changed it to "*The data acquired on 10 September 2009 was provided with Rational Polynomial Coefficients (RPC).*"

Page 7

Page 8

L14: "cf." not needed here and elsewhere. When citing a reference "cf" is implicit!!
Reply: OK, according to your suggestion we removed all "*cf.*" in the references of our manuscript to consult or see the cited material: *(cf. Mollberg, 1981); (cf. Pieczonka et al., 2013); (cf. Surazakov and Aizen, 2010; Pieczonka et al., 2013); (cf. Nuth and Kääb, 2011); (cf. Paul, 2008; Gardelle et al., 2012a); (cf. Pieczonka et al., 2013); (cf. Bolch et al., 2008; Pieczonka et al., 2011); (cf. Kääb et al., 2012); (cf. Shi et al., 2008); (cf. Yao et al., 2012); (cf. Schwitter and Raymond, 1993); (cf. Goldstein et al., 1993); (cf. Sharov et al., 2002); (cf. Floricioiu et al., 2010); (cf. Strozzi et al., 2002); (cf. Höhle and Höhle, 2009); (cf. Huss, 2013); (cf. Bolch et al., 2010); (cf. Seong et al., 2009a, b); (cf. Shi et al., 2008); (cf. Tian et al., 2006; Duan et al., 2007)).*

Page 9

L1: why "Terrain" why not simply "DEM"? would simplify and facilitate the reading (to avoid having two words for the same thing). Are two subsections 4.2.1 and 4.2.2 needed ? Not sure.
Reply: OK, we agree and renamed the section to "*4.2 DEM extraction".* Moreover, we omitted the heading of the two sub-sections as suggested

L22: check if "of" is needed here

Reply: We changed the sentence to "*Due to the lack of ephemeral or analogue metadata information the exterior orientation is solely based on 18 measured GCPs, by taking the earth curvature into account*."

Page 10

L3: I wonder how you can reach such low residuals using GCPs extracted from a 15 m Landsat image.
Reply: We received these values from the residual error report after DEM extraction by using the PCI Geomatica Orthoengine 2013 software package. The residuals were automatically calculated in ground units (meter) from the measured Ground Control Points during bundle block adjustment. We agree that the residuals are unexpectedly good and we can provide the entire residual reports of PCI if desired (please find below the relevant details):

Residual Error Report (ALOS PRISM)

Residual Units: Ground units

Residual Summary for 3 Images
GCPs: 17 X RMS 0.36 Y RMS 0.34
Check points: 0 X RMS Y RMS
Tie points: 217 X RMS 0.72 Y RMS 0.29

Residual Error Report (Pléiades)

Residual Units: Ground units

Residual Summary for 6 Images
GCPs: 33 X RMS 0.18 Y RMS 0.12
Check points: 2 X RMS 0.12 Y RMS 0.20
Tie points: 655 X RMS 0.07 Y RMS 0.07

L19: I somewhat ambiguous. What is the subject of the verb "were"
Reply: To be clearer, we changed the sentence and phrasing as follows: "*The thematic point status image of LPS showed that most calculated DEM points from KH-9 Hexagon (76%) were of fair quality with correlation scores ranging from 0.5 to 0.7. Of these points proved 17% to be of good and 7% to be of excellent accuracy, with coefficients higher than 0.85.*"

L26: rather "difference" than "error".
Reply: We think that the term "elevation error" is correct, because it is concerning wrong elevation values in the extracted DEM relative to the reference (DEM). The incorrect elevation is corrected "*based on the relationship between elevation difference and aspect*" as presented in the co-registration correction approach of Nuth and Kääb (2011). "Elevation difference" is, hence, already used some words later, and Nuth and Kääb (2011) also use the term "elevation error" in this context (e.g. : "*The relationship between elevation error and aspect has been…*")

Page 11

Page 12

L13: a bit strange. Why not "measured"?
Reply: OK, changed according to your suggestion

L16: strange wording. Why not "map of elevation difference (delta_h) calculated by differencing"?
Reply: We changed and shortened the sentence to: *"…are based on maps of elevation differences (δh) by subtracting older date elevations (e.g. KH-9 Hexagon) from newer ones (e.g. Pléiades)."*

L16: make sure acronym "delta_h" has been defined previously.
Reply: See previous comment.

Page 13

L13: a "elevation" is used before. I suggest keeping the same terminology.
Reply: We think that the word "thickness" in this context might be a better terminology to differentiate with DEM elevation changes in general, particularly off-glacier. However, we also agree that the terminology should not change during the manuscript. Hence, we changed the terms "glacier thickness change" to "glacier elevation change" in the manuscript at this position (page 13 L3) and at page 17 L6

Page 14

L4: why "topmost"? An ice layer, even below 1 m layer of cold transparent snow, will influence the penetration. By definition not only the surface matter but the upper snow/firn/ice layers below the surface.
Reply: We changed this sentence in view of that according to your suggestion: "*SRTM-3 C-band penetrations strongly depend on the condition of the upper snow/firn/ice layers below the glacier surface.*"

L11: I SEE THAT THE COMMENT BELOW HAS BEEN ADRESSED LATER IN THE MS. SKIP MY COMMENT. At this stage, I feel it would be unfair to ask you to take into account the much larger penetration depth infered by Kaab et al., TC, 2015 for the Pamir. But I think this deserves a word in the discussion to stress that this is a major source of uncertainties while using SRTM. One strength of your study is to provide long -term geodetic estimates independant of such an issue.
Reply: OK, comment skipped

Page 15

L7: I do not think surface velocities can be considered as "variations". So the section could be labelled just "Uncertainties"
Reply: Ok, just changed to "Uncertainties"

L13: what is it?
Reply: Not "adaption", but "adaptation" or "adjustment" of the reference outlines from Pléiades of 2013. We, however, omitted this word since it is not important at this step.

L20: again remove "cf" everywhere. wording to be improved (what is the subject for "is")
Reply: We removed all "cf." in the manuscript. We improved the wording to "*Similar to DEM co-registration, this calculation is based on DEM…*"

Page 16

L7: rather "results from"
Reply: Changed to "*results from*"

L9: "below"?
Reply: Yes, "below" is better

L16: maybe clarify in parenthesis what you understate (= both advanced and retreated over the study period).
Reply: Fluctuating is including advance and retreat, and a surge typically leads to rapid advance followed by shrinkage. Most of the glaciers showed a stable or continuously retreating glacier tongue. Some of the glaciers that fluctuated did finally also advance, but only very few only advanced without fluctuation. Hence, we set "advanced" in parenthesis since it is less pronounced in this study.

L23: not needed
Reply: Ok, omitted

Page 17

L2: I think "terminus" is more appropriate here.
Reply: Changed to *"…show a steep terminus…"*

L16: strange sentence. What is the subject of "was". Rephrase.
Reply: Changed to "*Despite its more or less stable tongue down-wasting was observed…*"

L24: "as" not needed
Reply: Omitted

Page 18

L2: "confluence" is maybe more conventional

Reply: Changed to "*confluence*"

L8: unclear to me what you mean by "lateral surface movements"?
Reply: With "*Lateral surface movements"* we meant at the glacier margin. Changed accordingly.

L24: be careful with negative values: your rates of length change are less negative (so there are higher!). I suggest using "not as negative"
Reply: Thank you for the hint. We changed "*is much lower compared to several*" to "*is not as negative compared to several*"

L25: same comments
Reply: We changed the entire sentence to "*We attribute the more negative rates of the aforementioned studies to the different sites and investigation periods*".

Page 19

L12: I suggest replacing by "glaciological mass balance"
Reply: True, changed accordingly

L19: authors need to list in a table the annual glaciological mass balances available for this glacier because to my knowledge they have not been published elsewhere. Also quote the cumulative mass balance from all glaciological measurements in the text and compare it to the geodetic value.
Reply: The annual glaciological mass balances have not been published elsewhere by now, this is correct. These in-situ measurements at Muztag Ata Glacier have been employed by our colleagues in China. We understand that a table summarizing the values of these measurements would be desirable. With our Chinese colleagues, however, we have agreed to publish their results in the way as it was done by now. We unfortunately cannot provide the annual values in a table, since the results need to be published by our Chinese colleagues first. We are in contact with our corresponding co-authors regarding this issue, but by now we do not have a positive response.

L19: ???
Reply: Changed from "*…after that…*" to "*…subsequently reassessed values for the previous period from 2005/2006 until 2009/2010…*". We meant that the previous mass balances (2005/2006 to 2009/2010) have been reassessed following the continued measurements with additional observations(2010/2011 to 2013/2014).

L23: IMPORTANT COMMENT:
In figure 3, the geodetic mass balance for this period is over 0.5 m w.e./year. No consistent with the text.
Reply: The geodetic mass balance for this period (over 0.5 m w.e./year in Figure 3) is presented for the entire Muztag Ata Massif and not just for Muztag Ata Glacier (see legend in Figure 3). This figure is presenting the cumulative instead of the annual mass balance, which was possibly not explained well or correctly. We therefore deleted the incorrect word "year" at the Y-axis of Figure 3b ("m w.e." instead of "m w.e. / year"). Moreover, we also modified the previously irritating (or wrong) figure capture to the following: *"(b) cumulative glaciological mass balance of Muztag Ata Glacier (G075058E38248N) vs. cumulative geodetic mass balance of the entire Muztag Ata massif"*. Please also have a look to our responses to your comments on Figure 3.

Page 20

L1: maybe quote their value?
Reply: Gardner et al. (2013) measured -0.13±0.22m a^{-1} and Kääb et al. (2015) measured -0.48±0.14m a^{-1} for the (west) Pamir. These values are now quoted in parenthesis, the text was slightly modified.

L4: I think the authors could also mention the different time periods as a possible reason. Indeed, GRACE data shows a strong mass gain after 2008/2009 (not captured by the ICESat studies) in this region (Yi and Sun, JGR, 2014) that may explain part of the differences.
Reply: We agree that different time periods might have influenced the deviation in results of these studies. The sentence was changed accordingly "*This deviation may be attributed to the different time periods of the studies and the uncertain penetration of SRTMs C-band radar into ice and snow."*

L15: increasing debris thicknesses (as written not obvious increase is for the debris cover)
Reply: Changed accordingly

L23: arguable analogy. because in your study, actually, rather stable terminus and limited area changes, are in "good agreement" with no significant mass change. So I do not think the analogy with glaciers losing mass (Fedtchenko or in Tien Shan) is relevant

Reply: This section is particularly addressing debris covered glaciers, as mentioned in the title: "*Down-wasting, surface dynamics and area changes of debris-covered glaciers*". Overall, for the entire massif, we observed that stable terminus positions and limited area changes are in mean in "good agreement" with no significant mass changes. This, however, is not the case for debris covered glaciers at Muztag Ata, which show indications of more pronounced mass loss. Particularly for debris covered Kekesayi Glacier, the moreover largest glacier of this massif (see later in the text), we observed mass loss and surface lowering at its tongue, despite a stable terminus position. We therefore think that such an analogy is worth to be set in context with e.g. Fedtchenko or Tien Shan.

L25: elsewhere, Pamir written without "s".
Reply: Changed to Pamir

Page 21

Page 22

L1: "a 41.6 m deep ice core" is maybe better
Reply: Changed accordingly

L6: at the summit? should not be negative then... Or for all glaciers in the Massif. Unclear right now, the description of these reconstrctued mass balance so need to be improved.
Reply: You are right, we are sorry for the confusion. Of course the snow accumulation is positive at the summit. Duan et al (2007) reports annual snow accumulation of about 0.62 m water equivalent on average on the peak of Muztag Ata, which decreased by a factor of two to three between 1958 and 2003. Based on these snow accumulation measurements and temperature recordings, Duan et al (2007) reconstructed mass balance rates "in Muztag Ata glacier" or the "glacier in Muztag Ata region". We assume that these statements concern the mass balances of the entire glaciated region at Muztag Ata as in our study. Unfortunately we do only have the abstract of this publication available and not the entire publication, which is presumably written in Chinese. To be more clear, we changed the sentence to "*Reconstructed mass balances rates of the glaciers in the Muztag Ata region do not agree with our results…"*

L9: but your data do not show such an accelerated shrinkage! Strange logic followed in this paragrap.
Reply: This assumption is stated in the cited studies of Khromova et al. (2006) (e.g. "*Glacier changes in the eastern Pamir are a response to increasing summer temperatures*" or *"…we consider it likely that these reductions in length and area were due to the observed increases in summer air temperature*") and Shangguan et al (2006) *(e.g. "…the rise in summer temperature after 1994, is the main forcing factor in glacier shrinkage.*" or *"… we believe that glacier retreat during the past 40 years can be attributed mainly to air-temperature rise in the Muztag Ata and Konggur mountains*"). To make it clearer that these statements are cited from these publications, we changed the sentence as follows: "*Accordingly*, *Khromova et al. (2006) and Shangguan et al. (2006) assume that further glacier shrinkage might have been accelerated by rising summer temperatures, particularly since the 1990s."*

L17 again, tortuous wording
Reply: Changed wording to: "*This relativizes the negative effects of climate change regarding warming and might be one of the reasons why average shrinkage and ice mass loss at Muztag Ata is low and insignificant."*

Page 23

L1: " are you refering to the KH-9 DEMs? I was uncertain
Reply: Yes, we are referring to KH-9. Changed to *"…and to that effect the relatively high NMAD of the KH-9 DEM is possibly overestimated*"

Page 24

L1: not really a good reason because summer is when the ablation is largest. If you compare a DEM from mid-June and mid-september (e.g. dates of the Pléiades vs ALOS) a strong seasonal correction is required (especially when the DEM are acquired just 4 years apart). This source of uncertainty (hard to quantify I reckon) need at least to be mentionned. The carefull examination of the overlapping area between the june/August Pleiades images could be useful to confirm that no seasonal correction is needed.
Reply: We agree to mention this uncertainty and corrected the corresponding sentence as follows, by moving it to the previous and more appropriate section "*Uncertainties of geodetic mass-balances from optical data*": "*Imagery for DEM extraction was acquired during summer months when snow accumulation is negligible, but when ablation occurs. Seasonal variations in glacier elevation change are taken into account by the conservative NMAD uncertainty estimate."*

Page 25

L1: Your wording suggest that this is because it is a large glacier that it experienced larger mass loss... Rephrase to avoid this wrong ambiguity. Large glaciers are not necessarily losing mass faster than smaller glaciers.

Reply: We agree that large glaciers are not necessarily losing mass faster as smaller ones. We try to avoid the wrong ambiguity by omitting the "as", resulting in this sentence: "*Kekesayi (G075225E38255N), the largest glacier at Muztag Ata, shows more negative trends…*"

Page 37

L1: I suggest putting this table as appendix. Thus, all these mass balance values will be included in the main article (not hidden in a supplement) but will not be to prominent and will not stop the flow of the reading of the article.

Reply: This is a good idea, and we agree to put this table in the appendix. Do we need to employ any changes in the manuscript for that?

Page 39

are these lines for the ELA? Should be distinguised from the outlines and added in the legend

Reply: These lines are outlines from mapping of glacier margins and ice divides. Black outlines are representing the glacier extend of 2013 in this figure. We excluded glaciated areas at very steep slopes in glacier mapping, which is particularly the case rearward the accumulation zone of Kekesayi Glacier, direction Muztag Ata peak (position of your comment placed in the figure). The ELA is shown in Figure 6, 7 and 8, the maps of elevation differences for different periods. In these figures you can also see in the hillshade (background) that this area is very steep.

Page 41

no title only (a) in the panel

Reply: OK, we omitted the title in the figure

same applies.

Reply: OK, we omitted the title in the figure

"," should be replaced by "." for decimals.

Reply: True, we employed these changes

I do not see the point in using a sort of spline interpolation between point of annual mass balance. I suggest showing the annual values (not the cumulative curve) and, with a line, the mean 2000-2013 value for easy visual comparison to the geodetic estimate

Reply: We agree and replaced the spline interpolation by a linear diagram. With our co-authors in China it was agreed to present their results in this way, but unfortunately we cannot include the annual values in this figure since the data is not published by our Chinese colleagues yet. Please see to this regard our response to your comments on page 19 L19. We think that presenting the cumulative glaciological mass balance of Muztag Ata Glacier is more significant and sound when comparing with the cumulative geodetic mass balance of the entire massif. The figure confirms a positive trend with mass gain by both the glaciological and the geodetic method.

Page 43

title of Y-axis should be "Elevation change 1973-2013 (m)". Stricting speaking, a negative down-wasting is... an elevation increase!

Reply: We agree to this and changed the title of the Y-axis of this figure to "Elevation change 1973-2013 (m)".

Page 44-46

rather "Map of elevation difference during..." or "Images of elevation difference".

Reply: Ok, changed accordingly to “Co-registered map of elevation differences during…” for all three figures (Figure 6 to 8).

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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

Previous ~~mass balance~~ in-situ measurements 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~~ amplitude tracking of TerraSAR-X images (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 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~~ the lowest 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~~ rates after 1999 ($+0.04 \pm 0.27\,\mathrm{m\,w.e.\,a}^{-1}$) are ~~confirmed by in-situ measurements~~ not significant, but confirmed by measurements in the field.

1 Introduction

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, while several glacier surges were observed 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 affects the ablation zones of almost all glaciers on the Tibetan Plateau (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).

In this study, we investigate four decades of glacier variations at Muztag Ata , 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 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 , situated in the most Eastern Pamir west of the Taklamakan Desert (Xinjiang Province, China). 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 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 cold valley glaciers are of the extremely continental type and accumulate snow mostly in winter (Shih et al., 1980; Maussion et al., 2014; Zhou et al., 2014). A roughly north-south trending high ridge and watershed divides the massif into a windward area with small valley glaciers exposed towards the westerlies and an eastern leeward part with higher gradientssteeper slopes. 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 Glacier is by far the largest glacier of this massif (Shangguan et al., 2006; Seong et al., 2009b, a; Yang et al., 2013).

Muztag Ata is situated in one of the driest glacierized areas of China and one of the coldest environments in these low- and mid-latitude regions

(Shangguan et al., 2006; Zhou et al., 2014). 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 mm (Yan et al., 2013b; Yang et al., 2013). The mean annual precipitation to Summer precipitation at the glacier accumulation zone at Muztag Ata is estimated to only account for 30 % of the total annual amount, which was measured to be ∼300 mm at 5910 m a.s.l. (38°42′ N, 75°01′ E) . Summer precipitation is estimated to only account for 30 % of the annual total (Seong et al., 2009b, a). (Seong et al., 2009b, a).

We used historical and state-of-the-art remote sensing datasets such as Hexagon KH-9 and Pléiades for 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 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.

2.1 Hexagon KH-9

Hexagon KH-9 was a photographic satellite surveillance system flown during 20 missions from June 1971 to April 1986 by the United States (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)~~(Mollberg, 1981). This is a 23 $\times$ 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 $\times$ 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~~ from the United States Geological Survey (USGS). Imagery with frame numbers 16–19 was recorded on 4 August 1973 during mission 1206-5.

2.2 Pléiades

~~The high resolution~~ Pléiades ~~satellite system was~~ is a high resolution satellite system 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. 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, 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.

2.3 ALOS-PRISM

The Japanese satellite system ALOS (Advanced Land Observing Satellite) operated from January 2006 to April 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. It offered 2.5 m spatial and 8-bits radiometric resolution with a swath width of 35 km in triplet mode. The ~~absolute geometric~~ location accuracy amounts to be 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~~ was provided with Rational Polynomial Coefficients (RPC).

2.4 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.

2.5 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).

2.6 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).

3 Data processing

3.1 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)~~(Pieczonka et al., 2013).

Prior to mosaicing, Wallis filtering with 51 $\times$ 51 pixels window size and histogram equalization was finally conducted for contrast enhancement (cf. Surazakov and Aizen, 2010; Pieczonka et al., 2013)(Surazakov and Aizen, 2010; Pieczonka e

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).

3.2 Terrain DEM extraction

3.2.1 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 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 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 18 GCPs for KH-9 Hexagon, ALOS-PRISM is covered by 6 GCPs and the Pléiades mosaic by 11 GCPs with at least 4 GCPs per scene.

3.2.1 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 potentially remaining film distortions. The principle-point offset was determined from the central reseau-cross coordinate to the midpoint of the image, which is defined by its extent. Due to the lack of ephemeral or analogue metadata information ~~is~~ the exterior orientation is solely based on 18 measured GCPs, by taking ~~in consideration of~~ the earth curvature into account. 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.

3.3 DEM post-processing

3.3.1 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 of fair quality with correlation scores ranging from 0.5 to 0.7. Beside these elevations of fair quality were Of these points proved 17 % to be of good and 7 % to be 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.

3.3.2 DEM co-registration

Horizontal DEM co-registration to SRTM-3 was conducted analytically by minimizing the elevation error based on the relationship between elevation difference and aspect (cf. Nuth and Kääb, 2011)(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)(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)(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)(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)(Bolch et al., 2008; Pieczonka et
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.

3.4 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).

4 Assessment of glacier variations

4.1 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. 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~~ measured along their central flow line.

4.2 Geodetic glacier mass-balance

Geodetic glacier mass-balances are based on maps of elevation differences (Δh~~pixels by differencing elevations of older dates~~) by subtracting older date elevations (e.g. KH-9 Hexagon) from ~~more recent elevations~~ newer ones (e.g. Pléiades). ~~Difference~~ Such difference images were generated for all possible DEM combinations of KH-9 Hexagon (1973), SRTM-3 (1999), ALOS-PRISM (2009) and Pléiades (2013). 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)~~(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~~ elevation 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.

4.2.1 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), based on estimations of the first Chinese Glacier Inventory ~~(cf. Shi et al., 2008)~~(Shi et al., 2008). ELAs were cross-checked in 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)~~(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)~~(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.

4.2.2 SRTM-3 C-band radar penetration

SRTM-3 C-band penetrations strongly depend on the ~~topmost glacier surfacecondition~~condition of the upper snow/firn/ice layers below the glacier surface. 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 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 ± 0.9 m for firn and snow (accumulation zone) and 1.5 ± 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.

4.3 Glacier surface velocities

Surface velocities of Kekesayi Glacier 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)~~ (Goldstein et al., 1993), GInSAR (Sharov et al., 2002) or double difference InSAR ~~(cf. Floricioiu et al., 2010)~~ (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 64×64 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)~~(Strozzi et al., 2002).

5 Uncertaintiesof 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)(Höhle and Höhle, 2009). Similar to DEM co-registration, is this calculation this calculation is 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)(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 results from the imprecise matching of the glacier surface features within the search windows. We measured residual velocities at a stable and plain surface after below the glacier terminus, where the channels carry the water discharge from the glacier. The RMSE was estimated over non-moving terrain of $\sim 5\,km^2$ to be ± 0.58 cm per day.

6 Results

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

6.1 Glacier area and length changes

The glaciers at Muztag Ata showed heterogeneous variations with some fluctuating ~~or advancing~~(or advancing), but mostly stable or continuously retreating glacier tongues 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) are heavily covered by debris and did not indicate any change at their frontal position. Average glacier retreat was observed to be $-1.0 \pm 0.3\,m\,a^{-1}$ from 1973 to 2013. Glacier length changes show decreasing and even positive values for later periods (Table 3). The determined overall shrinkage of $-0.6 \pm 3.9\,\%$ ($-0.02 \pm 0.1\,\%\,a^{-1}$) is ~~comparably~~ low and not significant. This corresponds to a glacier area reduction of $-1.6 \pm 10.6\,km^2$ from $274.3 \pm 10.6\,km^2$ in 1973 to $272.7 \pm 1.0\,km^2$ in 2013 (Table 4). The maximal extent of glaciation was observed to be at ~ 5000 m (Fig. 3).

Three south-western orientated glaciers (Kuosikulake, G075075E38189N and Kuokuosele) show ~~steep tongues~~ a steep terminus 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.

6.2 Geodetic glacier mass-balance

Glacier ~~thickness~~ elevation 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 was 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 $-0.03 \pm 0.33\,\mathrm{m\,w.e.\,a^{-1}}$ (1973–2009) to $-0.01 \pm 0.30\,\mathrm{m\,w.e.\,a^{-1}}$ (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 the characteristics of surface elevation changes continue well in line with our results from other periods.

6.3 Glacier surface velocities of Kekesayi Glacier

Surface velocities of Kekesayi (G075225E38255N) Glacier reached up to 20 cm per day in August 2011. This corresponds to a maximal flow of ∼70 m per year if a similar flow throughout the year would be assumed (Fig. 5). Ice flow at more than 15 cm per day (∼55 m a^{-1}) is maximal at its middle part, downstream of the ~~joining~~ confluence of the tributaries T2 and T3. ~~Lateral surface movements~~ Surface movements at the glacier margin, 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.

7 Discussion

7.1 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 in the central Pamir for the time period from 1972 to 2006 ~~in the central Pamir~~ (Kotlyakov et al., 2008). Contrary to this trend ~~was high shrinkage~~ high shrinkage was observed in the Zulumart Ranges south of Pamir Alay, where glaciers shrank −7.8 % (−0.65 % a^{-1}) from 1978 to 1990 which accelerated to −11.6 % (−1.05 % a^{-1}) until 2001 (Khromova et al., 2006). Shrinkage was also reported by Shangguan et al. (2006) at the Muztag Ata and Kongur massifs and was measured to be at −7.9 % (−0.21 % a^{-1}) from 1962 to 1999. 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 (−0.02 ± 0.1 % a^{-1}) and retreat (−1.0 ± 0.3 m a^{-1}) is ~~much lower~~ not as negative compared to several rates calculated per-glacier~~and to the aforementioned studies~~. We attribute ~~such higher rates~~ the more negative rates of the aforementioned studies 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)~~ (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) by reason of, on average, nearly balanced observed mass budgets in this study.

7.2 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~~ glaciological mass balance of $+0.25$ m w.e. a^{-1} from 2005/2006 to 2009/2010 by means of 13 measuring stakes for a small (size ~ 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~~ subsequently reassessed values for the previous 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~~ values 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) ($-0.13 \pm 0.22\,\mathrm{m\,a^{-1}}$) and Kääb et al. (2015) ($-0.48 \pm 0.14\,\mathrm{m\,a^{-1}}$) determined likely negative mass budgetselevation changes, based on the previously mentioned ICESat data, while Gardelle et al. (2013) found positive values . Gardelle et al. (2013) found a positive mass balance of $+0.14 \pm 0.13\,\mathrm{m\,w.e.\,a^{-1}}$ using SPOT and SRTM DEMs for the last decade. This deviation may be attributed to the different time periods of the studies and 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).

7.3 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 debris 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 debris covered 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 Pamir by far largest glacier, lost more than $-5\,km^3$ of volume during the last eight decades ($\sim -6.0\,\%$), 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 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.

7.4 Glacier response to climate change

From the Late Glacial to the Holocene, the glaciation style of the massif has changed from an expanded ice cap to deeply entrenched valley and cirque glaciers (Seong et al., 2009b, a). Recent glacier variations might be a response to changing atmospheric circulation patterns. Yao et al. (2012) observed strengthening westerlies coming along with an increase of precipitation, whereas the Indian monsoon is quite likely to weaken. Both temperature and precipitation in ~~this~~ the study region has been increasing (Shi et al., 2007; Qiu, 2014). In Xinjiang Province (North-West China), from 1961 to 2008 both mean annual temperature and precipitation increased per decade by +0.3 °C and +7.4 mm (Zhang et al., 2012). The summer temperature (June–August) at the close-by Taxkorgan meteorological station rose by +0.7 °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~~ a 41.6 m ~~in depth~~ deep ice core 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 °C per decade was observed, compared to Taxkorgan station measures at + 0.18°C per decade (Tian et al., 2006). Reconstructed mass balances rates of the glaciers in the Muztag Ata region 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 might, hence, have further accelerated glacier shrinkage~~ Accordingly, Khromova et al. (2006) and Shangguan et al. (2006) assume that further glacier shrinkage might have been accelerated by rising summer temperatures, 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)~~(Seong et al., 2009a, b). 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~~ . This relativizes the negative effects of climate change regarding warming ~~. This~~ and 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 Taxkorgan station (Shangguan et al., 2006).

7.5 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. 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 as compared to ALOS-PRISM (2.5 m, 8-bits), since its higher geometric (0.5 m) and radiometric (12-bits) resolution led to a lower rate of of poor elevation estimates. KH-9 Hexagon (6–9 m, 8-bits), moreover, shows high noise in its DEM at low-contrast terrain. Debris-covered and crevassed glacier surfaces, however, are of much better quality, and to that effect ~~its~~ the relatively high NMAD of the KH-9 DEM is possibly overestimated. Imagery for DEM extraction was acquired during summer months when snow accumulation is negligible, but when ablation occurs. Seasonal variations in glacier elevation change are taken into account by the conservative NMAD uncertainty estimate. 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 $\pm$6 m relative and $\pm$16 m absolute (Rabus et al., 2003). 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

Discussion Paper |
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Discussion Paper |

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

7.6 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. 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.~~

8 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. 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 a potentially underestimated SRTM-3 C-band penetration into snow and ice. Slightly positive observed budgets after 1999, however, 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 ~ 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. This study presents, in combination with the recently recorded high-resolution Pléiades imagery, 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 (Shi et al., 2008)

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

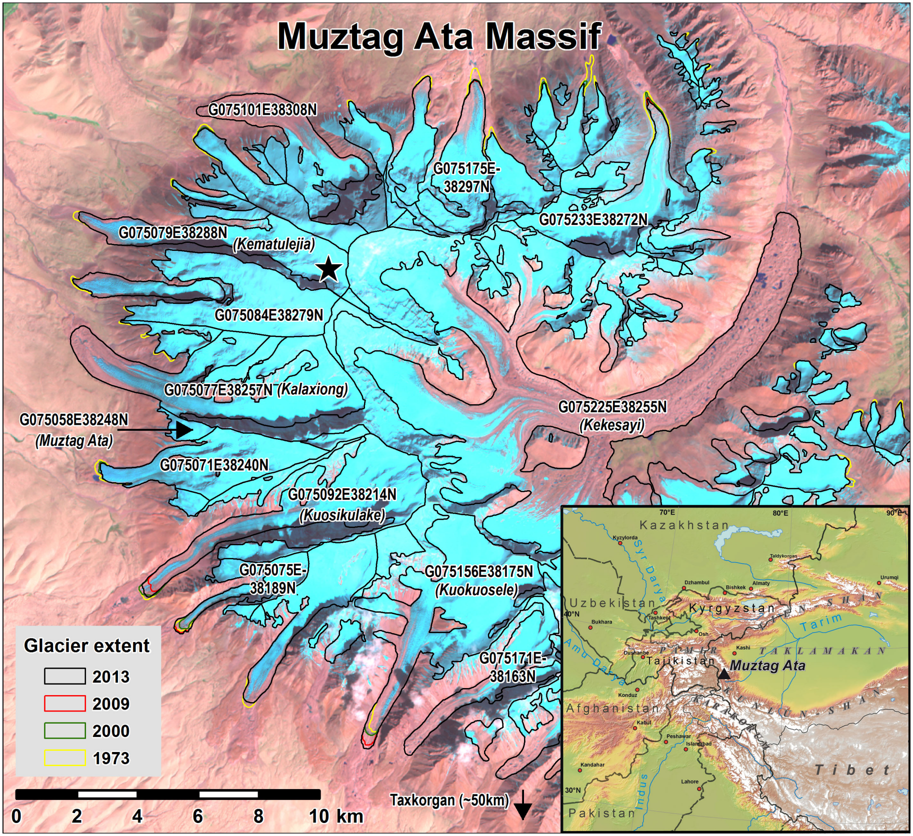

Figure 1. Overview of the Muztag Ata study site with investigated glaciers according to their ID in GLIMS (background image: Landsat 7 ETM+ of 11 September 2000; *: ice core location ~~(cf. Tian et al., 2006; Duan et al., 2007)~~(Tian et al., 2006; Duan et al., 2007)).

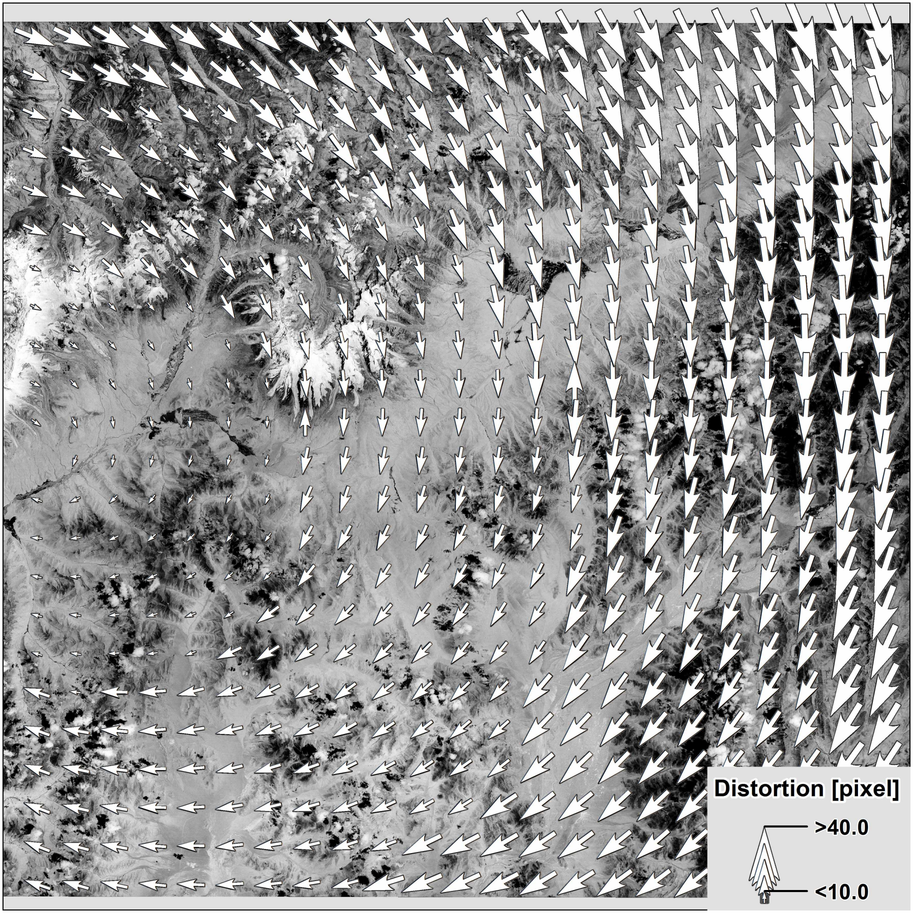

Figure 2. Distortion vectors of reseau-crosses from their measured to their initial reference positions in a KH-9 photograph segment covering Muztag Ata (frame 17a of mission 1206-5).

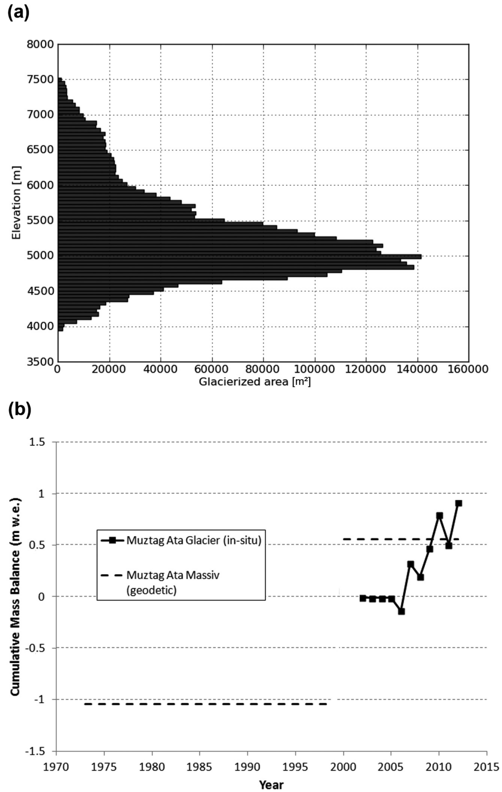

Figure 3. (a) Hypsometry of the glacierized area at Muztag Ata, **(b)** cumulative ~~vs. in-situ measured~~ glaciological mass balance ~~for~~ of Muztag Ata Glacier (G075058E38248N) ~~and~~ vs. cumulative geodetic mass balance of the entire Muztag Ata massif.

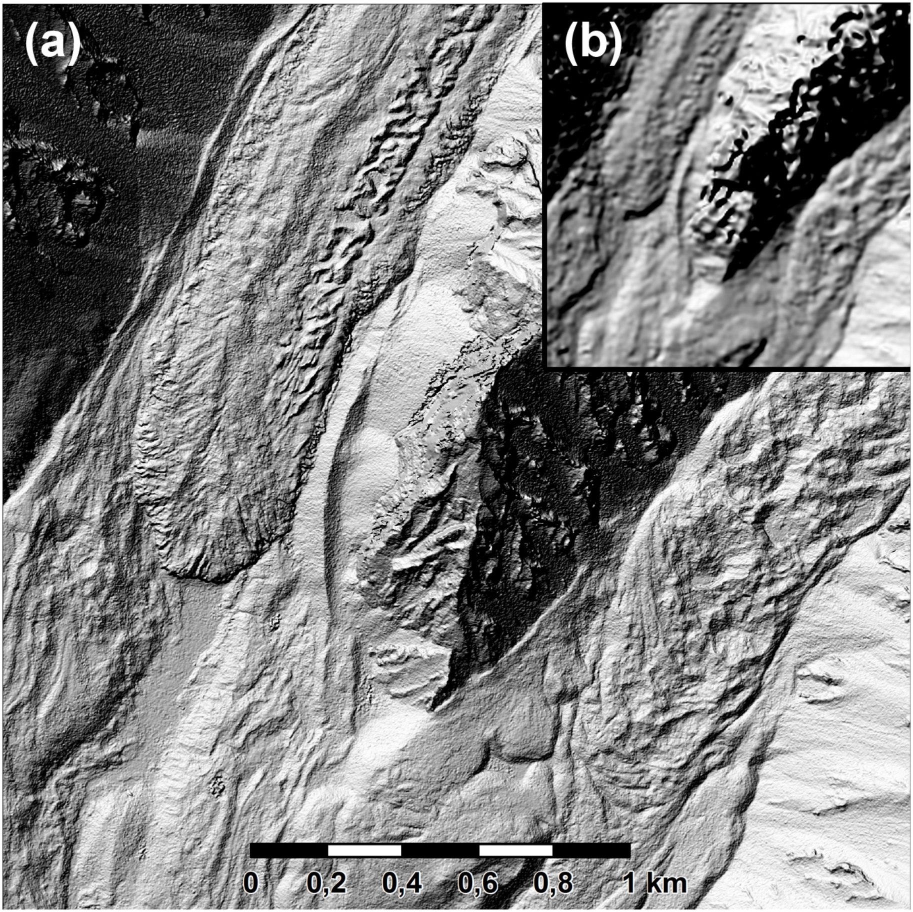

Figure 4. (a) Hillshade of the Pléiades DEM at 1 m resolution with advancing tongue of Kuokuosele Glacier (G075156E38175N, left) and stable tongue of glacier G075171E38163N (right), **(b)** compared to 10 m DEM of ALOS-PRISM.

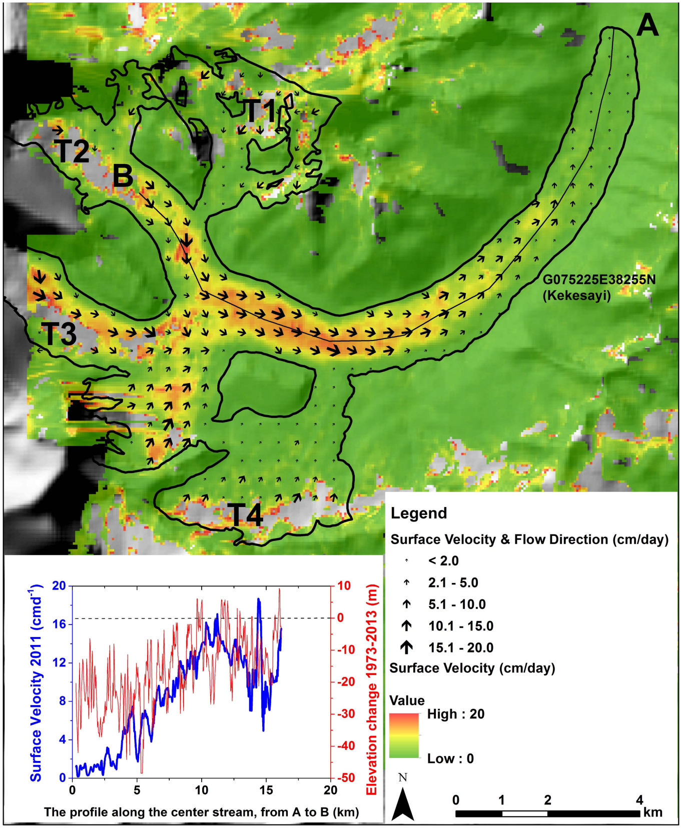

Figure 5. Surface velocities and flow directions of Kekesayi (G075225E38255N) Glacier in August 2011. The profile shows the surface velocities and the corresponding down-wasting (1973–2013) along the central glacier flow line, upstream from A to B.

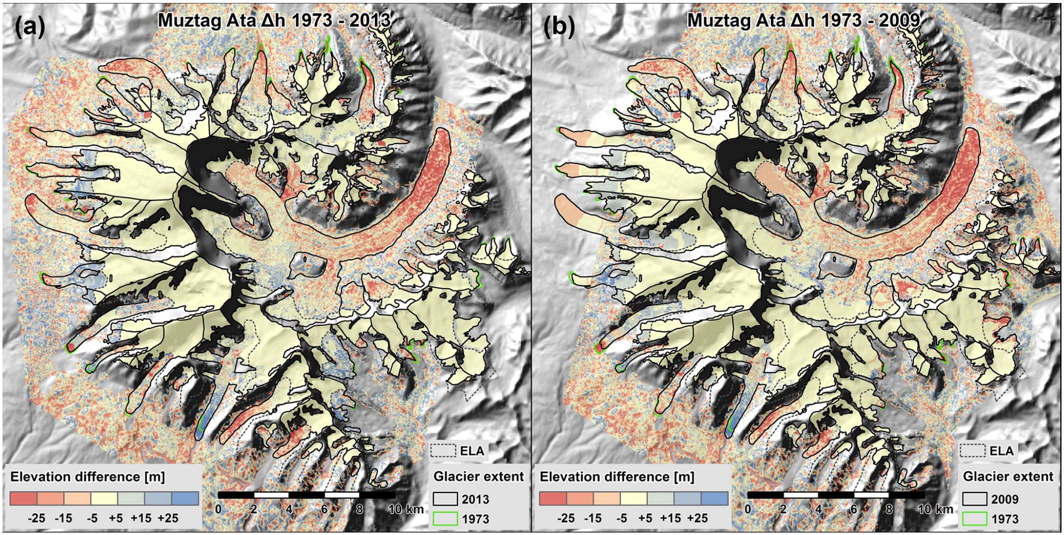

Figure 6. Co-registered ~~difference images~~ map of elevation differences during 1973–2013 **(a)** and 1973–2009 **(b)** after outlier and gap-filling processing for glacier mass-balance and vertical uncertainty calculation (ELA adapted from Shi et al. (2008)).

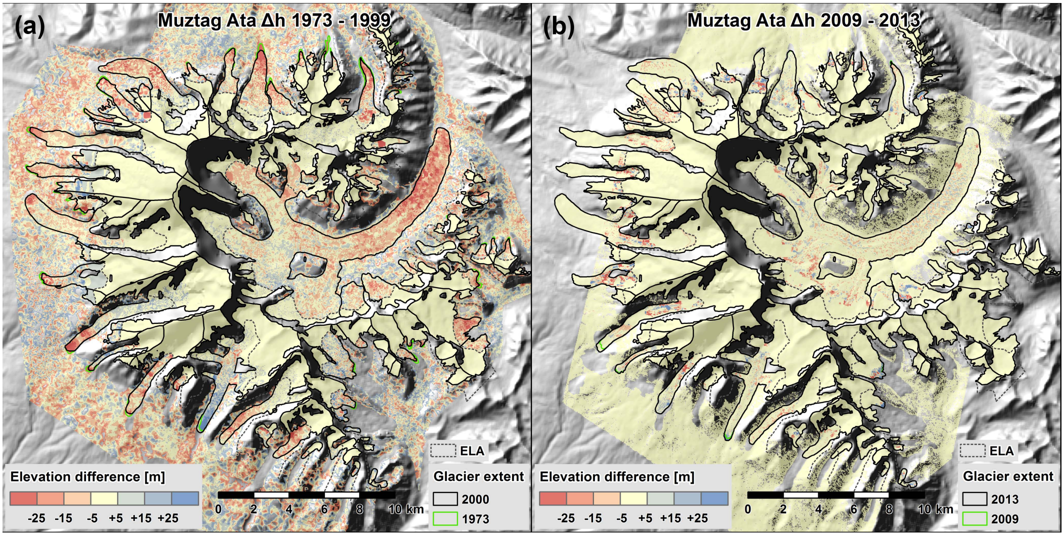

Figure 7. Co-registered ~~difference images~~ map of elevation differences during 1973–1999 **(a)** and 2009–2013 **(b)** after outlier and gap-filling processing for glacier mass-balance and vertical uncertainty calculation (ELA adapted from Shi et al. (2008)).

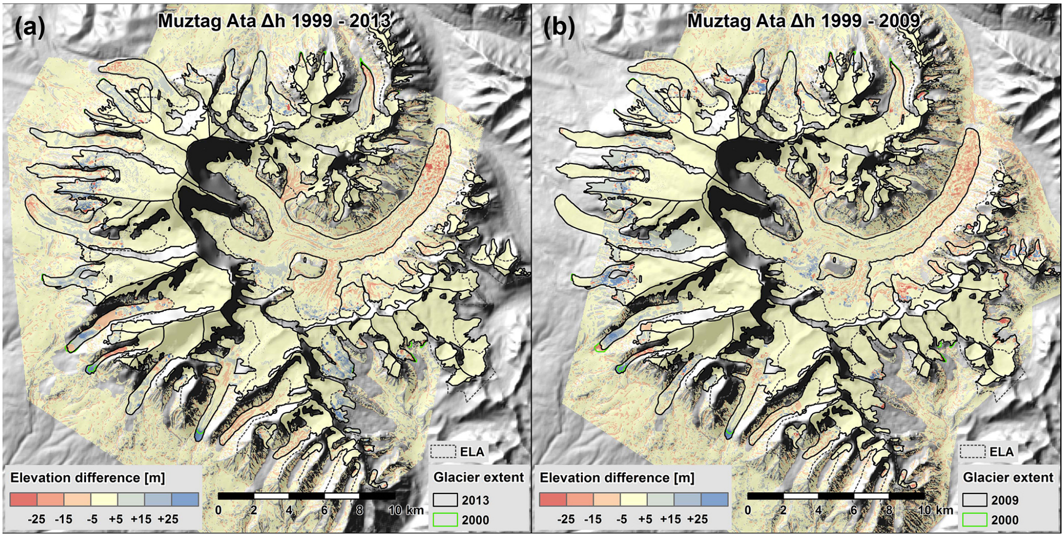

Figure 8. Co-registered ~~difference images~~ map of elevation differences during 1999–2013 **(a)** and 1999–2009 **(b)** after outlier and gap-filling processing for glacier mass-balance and vertical uncertainty calculation (ELA adapted from Shi et al. (2008)).