Reviewer 1

Review for the paper by Shangguan "Mass changes of the Southern and Northern Inylchek Glacier, Central Tian Shan, Kyrgyzstan during ~1975 and 2007 derived from remote sensing data", The Cryosphere Discuss

The paper has undergone some revisions and improvements since the last submission, but still shows considerable deficiencies. Not all points of critics have appropriately been addressed (e.g. quality of the figures). The error bars for the extent mapping and velocities are not yet well explained. The assumption of zero-penetration of the x-band SAR signal in dry snow for the SRTM is not correct in my view and needs revision of text and computations. References in the intervals of volume and mass changes are not consistent throughout the manuscript and this makes reading and verification what actually has been done very difficult (e.g. has DEM2007 been subtracted from DEM1999 or vice versa. This does not become clear due to completely opposite labeling in text and fig.4. This matters in regard to the sign and direction of changes observed as well as the interpretation presented!). The figure numbering is not according to the appearance in the text and needs to be adjusted. Most of the figures are still in an unacceptable state and partly labels referred to in the description cannot be identified. This has been addressed in the previous review and only partly been changed by the authors. Final proof-reading by a native speaker would omit missing or incomplete phrases as present at various locations in the manuscript. My judgment is between major revisions and rejection since the authors failed to provide a proper revised manuscript that at least adheres to basic, technical and formal standards. There can of course still be small issues and one might see things different. However, for a paper in the state of revisions I would expect that at least such formal criteria like clear figures, figure sequence and reasonable correct grammar and language are met. I leave it to the editor to decide if he want to proceed with revisions or reject. In any case, the manuscript needs considerable rework.

Reply: We apologize that we did not revise our manuscript and the figures careful enough and are thankful to the editor that we got the chance to do so in this revision. We have now improved the quality and clarity of the figures, addressed all comments and carefully proofread the manuscript by ourselves. Finally, a native speaker polished the English.

Specific comments:

L24: this sentence reads like you analyzed a long time series, but in fact is was a bitemporal comparison. So please reword

Reply: The sentence was changed to "Velocities of SIG in central part of ablation region reached ~100 - 120 m/a in 2002/2003 which was slightly higher than the average velocity in 2010/2011 with the main flow direction towards Lake Merzbacher."(See page 1, line 25f) ".

L25: … SIG tongue/terminus …???

Reply: It was SIG terminus. In the manuscript "at the end of tongue" was changed to "at the distal part of the terminus".

L26: "likely" ==> what does this mean – did you measure the velocities or not? Are they outside of the error bars, then why likely, when inside, its not a major result to be stated in the abstract. Knowing this, what's about the directions which often are even less reliable when the velocity is already difficult to measure. So perhaps better delete L25?

Reply: Thank you for your comment. We used "likely" as our results indicate very low or now flow velocities. We write now: "The measured velocities at the distal part of the terminus downstream of Lake Merzbacher were below the uncertainty, indicating very low flow with even stagnant parts." .

L27: Better write "Geodetic glacier mass balances" instead of "Glacier mass balances"

Reply: Agreed. It was changed to "Geodetic glacier mass balances".

L35/36: This last sentence is strange and without connection. It needs more explanation. A phrase of conclusions is missing in the abstract as do 1-2 sentences of the critical discussion. So perhaps really delete the uncertain velocities of the glacier front and put 2 phrases on discussion and conclusions.

Reply: Thank you for your comment. The sentence was changed to "In contrast significant thinning (>0.5 m a^{-1}) and comparatively high velocities close to the dam of Lake Merzbacher were observed for SIG, indicating that Lake Merzbacher enhances glacier mass loss." (line 37). The uncertainty velocities of the glacier front was evaluated in section 3.3 (see line197)

In discussion section, we mentioned the ice calving, fast elevation changes, comparatively high velocities, then we assumed the lake enhance glacier mass loss (see line 408 - 410). We also added two sentences were in the conclusion (line 499 - 501).

L45/46: I think this sentence "On average, ..." is somehow misplaced here as it has no real connection to the phrases before or after. So move it somewhere appropriate (e.g. L51).

Reply: Agreed. The sentence was not necessary and was repeated in section 5.2 (line 395). Thus, the sentence was deleted here.

L46/47: "The runoff . has increased during the last decreased" ==> I do not understand this sentence nor do I believe the cited authors have written it as such. Please verify.

Reply: Sorry, "decreased" was a slip of the pen. It was changed to "decades".

L53-62: Is this not standard textbook information that might be omitted to make the manuscript more concise?

Reply: We omitted the sentence "However, area changes show only indirect, filtered and delayed signals of climate change (cuffey and Paterson, 2010)…, lower changes in area compared to temperate glaciers,".

L70: Insert a paragraph break before "SIG, the ..."

Reply: It was done. In addition, combined the next paragraph with this paragraph together (See line 71).

L79: Delete "also" in this phrase

Reply: "Also" was deleted.

L98: … the glacier flow at the terminus is mainly directed towards …

Reply: Sorry, we meant that glacier flow in the central part of the tongue is mainly directed towards…. The two sentences were combined together and we write now: "Existing velocity measurements of SIG show surface velocities of about 100 m a-1 for the central part of the ablation (Li et al., 2013; Nobakht et al., 2014) where the glacier flow is mainly directed towards Lake Merzbacher (Mayer et al., 2008, Nobakht et al., 2014). " (see line 93 - 95).

L120ff: Please do not repeat information in the text that is also given in Tab.1 (e.g. spatial resolution, ground coverage).

Reply: Thank you for your comments. We deleted this sentence "Each scene is characterized by a spatial resolution of about 20 - 30 feet (6 - 9 m) with 240 x 120 km2 ground coverage (Surazakov et al., 2010; Pieczonka et al., 2013)."

L138ff: Please do not repeat statements given in Tab.1 like B/H ratio of SPOT. I suggest to concentrate all information on the data (incl. incident angles) in Tab.1 and only refer to general info in the text. This makes Tab.1 the one and only point to find the information and not spread over text and table. Similar for ALOS.

Reply: Thank you for your suggestion. We have updated two paragraphs. We deleted the B/H-ratio of SPOT and ALOS in the text. The information of incident angles was only used to calculate the B/H for SPOT HRG. So, we prefer to keep the information of incident angles in the paragraph.

L148: reference to Fig.4 does not follow the order of appearance in the text. This is confusing and I suppose automatic referencing during the type setting will mess this up. So please decide on order and when you refer to figures.

Reply: We are so sorry to make this mistake. We deleted the “See Fig. 4”.

L158: again order of figure reference is not correct

Reply: Showing Fig. 3 was not necessary. Hence, we deleted “the Figure”.

L165: now fig.2 appears...

Reply: It was correct.

L170ff: I still do not agree on the detection accuracy of half a Landsat pixel, although the authors outline their point in the response to the reviewers. This might be true in some cases, but not overall. Their own statement in the present manuscript relates to difficulties with debris cover and they use a hillshade based on the 90m SRTM DEM to improve the detection. Hence, I doubt that the detection accuracy can be 15m (half a Landsat pixel) or something is misstated or I misunderstood the procedure completely.

Reply: We are aware that our uncertainty estimate is a theoretical measure, but it is well justified and widely used by other studies. You can detect the glacier boundary with an accuracy of half a pixel in case of clean ice and good snow conditions. However, we agree that it is more difficult with the debris-covered parts. In this case, we set now a buffer of 2 pixels to evaluate the delineation uncertainty. We had also higher resolution data (such as SPOT, ALOS PRISM) which help to identify the margin.

L175ff: The error terms for absolute image registration are not stated or is this included in the percentage value given? It cannot be known from the write-up. Perhaps it would be easier to read when the errors are given in a short table rather than in the text.

It appears that error bars are kept smaller than they really are. Actually larger error bars wouldn't be any problem in my view but perhaps be more realistic?

Reply: We used the orthorecitified images. The uncertainty due to image co-registration is captured with the buffer method and included in the percentage value given. We have included this information now in the manuscript (see line 169 - 171). The table 2 (uncertainty of glacier delineation) was added. We fully agree with your opinion that error bars should be realistic. We also compared the uncertainty with the approach suggested by Pfeffer et al. (2014, Journal of Glaciology), the uncertainty was calculated by using the formula: $e(s)=k*e*S^p$(k=3; e=0.039;p=0.7). Delineation uncertainty of SIG in 30 m resolution was about 9 km^2. Our results was 2.2%*508km^2=11.2. Both Pfeffer's and our results were comparable; hence we think our result provides a reliable uncertainty estimate.

In addition, we use 1 pixel for hexagon in bare ice and snow condition due to the lower accuracy of the registration (see section 5.1).

L182: What are glacier velocity rates? Do you mean displacement rates – that would be the velocity or not?

Reply: We write now displacement rates.

L185/186: This sentence is incomplete (point) and doubles the statement in L184. Please revise this section or delete this sentence.

Rep**ly:** Yes, the period signal was lost between "in Cosi-corr" and "For ASTER". The sentences were changed to "A frequency based feature tracking (phase correlation) was performed using the EXELIS VIS ENVI add-on COSI-Corr in order to get the horizontal offset of corresponding image points. The tracking was performed using the method of phase correlation. For ASTER data…".

"

L188: In the data section you mention that SRTM 4 was gap filled and you also use SRTM3 plus the unfilled finished-B SRTM. It now becomes confusing to the reader what SRTM DEM you use for what purpose and why. Please make this clear – best already in the data section/Table!

Rep**ly**: Fully agreed. In table 1, we added the information of SRTM 3. And in section 3.1 the second paragraph, the sentence "The void filled SRTM3 DEM was used for the orthorectification of ASTER images and the calculation of the glacier hypsometry (Supplementary Figure S2)." was added.

L190: I think the grammar is not right here, do you mean “Dependent on an expected image ...”

Repl**y**: Yes, it was changed to “On the basis of an expected annual average velocity of…”

L200: There is a blank behind “SIG, “and before the comma. What data is used to compute the RMSE and how are observations taken into account?

Reply: For accuracy assessment, we calculated RMSE value, which was determined by an analysis of significant displacements/ velocities, as parameter for erroneousness. Conciseness is derived by the ratio of RMSE and the resolution of the respective input data.

As well as Inylchek Glacier, some nearby glaciers were observed with the named input datasets. The calculation of the RMSE values considers all observations. Therefore the survey compasses a huge amount of significant and non-significant velocity dates, which allows a solid accuracy assessment.

L201ff: The following 2 phrases are unclear – e.g. “..., the survey compasses...”. Please reformulate.

Reply: The two sentences were not necessary. Hence, they were deleted.

L204/205: How are these uncertainties estimated? Could you please provide a similar error estimate/propagation as for the area changes.

Reply: The written values are concered with the illustrated input data and the used tracking method. The last sentence was changed to “The final significance has been determined to be 3.5 m/a for 2002/2003 and 4.7 m/a for 2010/2011 in respect of the RMSE.”

L230: This might better read “The accuracies of the final DEM differences were evaluated ...”

Repl**y**: Thank you for your comments. This sentence was updated to “The accuracies of the final DEM differences were evaluated…”.

L249ff: The assumption of negligible X-band penetration in dry snow is wrong. It does not help to give a reference here that also relies on other references or comes from optical remote sensing. Please provide information on original surveys of X-band penetration studies of snow (e.g. by Matzler) or to standard text books. Check also the observation principle of the former ESA CoreH2O Earth explorer candidate mission (X- and Ku-band to measure SWE of dry snow) or observations from the TanDEM-X mission of snow and glacier areas e.g. in regard to laser scanning also laser altimetry. The X-band penetration is just different/less to C-band, but not zero or close to zero under dry snow conditions (different when wet of course)! This section and computations require revision.

Repl**y**: Thank you for your comments. We are aware about the penetrating problem. However, it was suggested by the literature (Gardelle et al., 2012) to use the difference between the two DEMs as an approximation of the c-band penetration. To avoid this issue we have now processed the available ICESat GLA 14 data comprising 6 tracks and compared them to the SRTM C-band data. The result showed an penetration depth of 6.8 ± 2.1 m which is significantly higher than the previously estimated penetration depth of 4.2 ± 1.9 m. We also re-evaluated the uncertainty of the elevation differences. In addition, the references of Matzler and Wiesmann (1999) and Surdyk (2002) were added.

L268: The time difference between the survey and the DEMs is partly really considerable and the errors resulting from ablation cannot be evaluated. I suggest to give not only the deviations of the SPOT model but also the values for the used SRTM, ALOS and KH-9 DEMs in Tab.3.

Repl**y**: Thank you for your suggestion. Now, we used ICESat GLA 14 data. Therefore the GPS points are not necessary and we deleted those contents (errors due to ablation between 2006 and 2007, and also ALOS, KH-9 in manuscript.

L296: Again check the order of figures as they appear in the text.

Rep**ly**: We replaced “Figure 6” with “altitude zone”. In addition, the next sentence was deleted because it is not suitable in method’s section. It was shifted to the discussion’ section.

L311ff: However, Fig.3 shows also flow vectors into the glacier tongue although the magnitude is higher towards lake Merzbacher. But does this mean that the main flow direction is towards the lake? In Fig.3b, there is an obvious low flow section exactly at point b, upstream of the turn to lake Merzbacher. This is not addressed in the text, can this feature be explained or is it a tracking error?

Rep**ly**: The main flow is towards Lake Merzbacher and glacier terminus in central ablation region and is towards the glacier terminus in lower ablation region. The obvious low flow section was mentioned in manuscript (see page 12, line 347). However, it was sure that low flow section is not tracking error because other results from Nobakht et al. (2014) and Neelmeijer et al.(2014) were similar with our results. Low flow section may be dammed by downstream.

L321: Perhaps better replace “shrank” by “retreated”

Rep**ly**: We refer to a reduction in area and not in length; hence, “shrank” is the correct term.

L321ff: The number given here could perhaps also be given as mean annual retreat rates since this allows a better comparison between the different long observation periods. The numbers are also given in Tab.4 – so either specify them in the text or in the table but not double the information, and even with different signs in the text and table – this is confusing!

Rep**ly**: Thank you for your suggestion. The mean annual retreat rates were calculated, however, the percentage was too small to be provided. We use the signs now consistently.

L332ff: It would be nice to give the original value of volume loss per elevation zone, since there might be other conversions of volume to mass coming up and the current data provided does not really allow subsequent utilization with different conversion factors. Again the values given in Tab.5 are also stated in the text – so either/or. The signs of the values are again different in table and text. I understand that the authors want to avoid writing about a negative mass loss, but it somehow is confusing when mass loss is attributed as loss of 0.3 m w.e a-1 and on the other hand a possible positive or balanced budget is given with -0.1 (L336).

Repl**y**: A supplementary Table S2 was added to show the elevation difference per elevation zone. We also updated the signs of the values. We do not want to avoid the mass budget by using positive or negative. The mean of "the mass loss of SIG and of NIG was about 0.3 ± 0.1 m w.e.a-1 and 0.5 ± 0.1m w.e.a-1, "is same as " the mass budget of SIG and of NIG was about -0.3 ± 0.1 m w.e.a-1 and -0.5 ± 0.1m w.e.a-1, ". We only avoided the repeat in sentence because the next sentence is "the mass budget of ….".

L337: What does the expression elevation thinning mean? Is this different from thinning or elevation decrease?

Repl**y**: "elevation thinning" was changed to "significant thinning".

L339/340: This is interpretation and should be left/moved to the discussion

Repl**y**: Thank you for your suggestion. "Thus, the significant…" was moved to the discussion.

L341: Please verify grammar

Repl**y**: It was changed to "The elevation differences measured along…"

L345: Should read “which are”

Reply: Thank you for your comments. It was changed to “which are”.

L341ff: The labeling of the figure and terminology in the text are not consistent. In the text the authors speak of surface lowering between 1975-1999 while the figure shows this as 1999-1974. This makes it unclear and very confusing what is shown and what has been subtracted from what and even the years are different! It influences the sign of the observations and hence all the description. Please be consistent throughout the manuscript in regard to terminology/labeling and signs including the figures. Figure 5 caption depicts 1975-1999 while the legend shows SPOT-KH9 – so what is right? Please clarify.

Reply: Thank you for your comments. In the first submission we had only data from 1974. Now we added data from 1976. Hence, we refer now to the mean year 1975 and all the periods were changed to ~1975-1999, 1999 – 2007 and ~1975 - 2007. The Figure 5 caption was changed to KH-9 – SRTM (~1975-1999).

L347/348: “... while a slight decrease with small amplitudes ...”. Is there also the option for a slight decrease with high amplitude?

Reply: Yes. We changed the expression to “Between points b and g a clear surface lowering could be observed for the period ~1975 - 1999 and 1999 - 2007 (Fig. 4 and Fig. 5).

L350: Do not start a sentence with “and” please ==> rephrase

Reply: “And” was deleted.

L352: “...where the velocity was faster measured ...” I suppose you mean high velocities were measured, not that your activity of measuring was faster.

Reply: Thank you for your comments. We updated it as “An apparent elevation increase at a mean rate of 1 - 2 m a^{-1} was observed for the period 1999 - 2007 in region 2 (above point g) of the accumulation region for SIG (Fig. 4b) where decreased velocities were measured for the period 2002 - 2003 and 2011 – 2012 (Fig. 3a). ” (see line 350)

L353: “It looks like a tributary surge”. You are still presenting results, but start speculating. This is clearly a sentence that needs to be moved to the discussion.

Repl**y**: Agreed. It was deleted because the second reviewer advised that it is not necessary to consider it as a tributary surge. The possibility of tributary surge is now mentioned in the discussion section (see line 438-451).

L359: Again, assumptions should not be presented in the result section but might be part of your discussion and interpretation of the results.

Repl**y**: The strong advance is a clear indicator for a surge. We think this is an important result and should also be mentioned here. We write now “The clear thickening at the tongue of NIG and a lowering in higher altitudes (Fig. 5) together with the data of area and length change are a clear indicator for a surge event that happened between 1990 and 1999.” and moved this sentence to discussion section. See line 436.

L368: “... the elevation of the SIG was thinning under ...” - this reads as if the altitude was actively thinning. Please rephrase.

Repl**y**: It was changed to “… the elevation of the SIG decreased under…”

L362: Wouldn't it be more comprehensive to start the description with the earliest time interval and then go to more recent one or the overall period. This approach is not consistent in the manuscript, but would ease reading and help following the authors argumentations quite a bit.

Repl**y**: Agreed. This paragraph was rephrased according to earliest time interval (~1975 – 1999), more recent (1999 -2007) and then overall period (~1975 -2007).

L378f: It might be worth starting with an interpretation and discussion of your results rather than presenting numbers of other observations over several lines that have already been mentioned in the introduction. So rearrange the text – mention your observations and if/how they are in line or contrast to previous work.

Repl**y**: Thank you for your suggestion. This paragraph was rephrased to “Our study revealed only a slight retreat of SIG during ~1975 and 2007 while a strong advance for NIG could be identified between 1990 and 2000. Osmonov et al. (2013) reported an average shrinkage of 3.7 ± 2.7% from 1990 to 2010. Our results tend to be in agreement with Osmonov et al. (2013) who, however, did not analyse SIG and NIG separately and did not report the NIG surge. Glacier shrinkage in adjacent regions such as, in Northern Tien Shan (Bolch 2007, Aizen et al. 2006), or eastern/Chinese part of Tian Shan (Ding et al., 2006), was significantly larger.”.

L390ff: The observations and temporal variability of glacier surface velocities has also been identified by high-resolution TerraSAR-X imagery. I think it is mandatory to refer to the work by Neelmeijer et al. (2014) – actually on the authors has coauthored the work by Neelmeijer et al. - so even more astonishing that this is not mentioned.

Repl**y**: We now refer to (Neelmeijer et al. 2014).

L396: “huge” - this is not a good expression here as the relations do not become clear – better address like XX m/yr or XX% of the overall mass loss …

Repl**y**: Agreed. The sentence was changed to “the elevation changes were about-0.5 - -2.0 m a^{-1} for the periods ~1975 - 1999 and 1999 - 2007 near the lake dam”

L397/398: “flow velocities at the middle part of the SIG tongue were higher that at parts” ==> please verify grammar, wording and sense of this phrase.

Reply: Thank you for your comment. The sentence was changed to "Flow velocities at the central ablation region of SIG (between point b and point c) were higher than between point a and point b (Fig. 3)."

L399: "High velocities transports ..." check grammar

Reply: It was changed to "High velocities transport"

L400: Do you mean water from the Lake Merzbacher lubricates the glacier bed? One might doubt this and any proof of that is missing nor reference to comparable situations. Could this not also just be enhanced melt at the front? Actually also change the expression "glacier base bed". Please check also the paper of Neelmeijer et al. (2014) where high-resolution flow fields are provided over entire melt periods.

Reply: Thank you for your comments. It is good suggestion. "glacier base bed" was changed to "glacier bed".

In this section, we discussed the activity of lake. And it is likely that water of lake Merzbacher lubricated the glacier bed close to the lake dam. We have now cited Neelmeijer et al. (2014). Proglacial lakes also enhance melt which is likely why large thinning close to lake dam can be observed.

L409: "... it could be brought uncertainty though we ..." ==> please check grammar and wording

Reply: The sentence was changed to "Another source of uncertainty is the different acquisition time of the KH-9 images. We used therefore mean annual elevation changes to calculate mass balance."

L422: Please check wording and grammar

Reply: This sentence was changed to "The mass balance from Kara Batkak and Tuyuksu glaciers, for instance, was -0.77 m w.e.a-1 and -0.59 m w.e.a-1 between 1974 and 1990, " (see line 422-423).

L424: "However, it is disagreement on the mass balance of ..." ==> please check grammar

Reply: Due to the new mass balance results, this sentence was updated to "The mass balance from Karabatkak and Tuyuksu Glaciers, for instance, was -0.77 m a-1 and -0.59 m a-1 from 1974 - 1990, respectively and the mass balance of Tuyuksu glacier was -0.35 m w.e.a-1 from 1999 to 2007 (Unger-Shayesteh et al., 2013; WGMS 2013; Cao, 1998). The tendency of Tuyuksu glacier mass balance was in line with SIG for which found on average mass loss (-0.43 ± 0.08 m w.e. a-1) during ~1975 - 1999 followed by an decelerating mass loss (-0.28 ± 0.44 m w.e. a-1) during 1999 -2007. However, the mass balance of the Urumqi Glacier No.1 was -0.24 m w.e.a-1 during 1975 - 1999, and -0.63 m w.e. a-1 during 1999 - 2007 (Wang et al., 2012). This tendency is in line with our results for NIG for which found on average a mass loss (-0.25 ± 0.08 m w.e. a^{-1}) during ~1975 – 1999 followed by an accelerating mass loss (-0.57 ± 0.44 m w.e. a^{-1}) during 1999 – 2007.

L443: "... mass displacement down-glacier is an important signal that occurs before a glacier surge" ==> The mechanism stated here remains unclear to me since flow speeds are generally highest during a surge (e.g. Quincey et al. 2011) and one would expect considerable mass relocated during the surge event. So what causes a significant mass transport BEFORE the surge without increased ice dynamics and how would that drive a surge afterwards?

Reply: According to two reviewers' two suggestion, we decided that we deleted the tributary surging. For the explanation, please see below (L445).

L445: Cuffey & Paterson (2010) is a textbook. Are you sure that they present there original own results or rather cite work? ==> in case rephrase

Reply: Agreed. We put the sentence "Our results agreed with that mass displacement down-glacier was an important signal that occurs during a glacier surge and glacier surging will re-distribute glacier mass (Dolgoushin and Osipova, 1975)" after the first sentence in this paragraph. We also deleted the reference (Cuffey & Paterson,2010)

L449/450: Please check logic in this sentence. I also do not understand how low flow velocities are necessarily linked with high ablation/melt down rates. Couldn't there be high ablation rates and high velocities?

Reply: Thank you for your comments. Here, we explain the reason of premature. In the last sentence of this paragraph was changed to “Therefore, the significant mass loss in debris-cover region can be explained by the influence of backwasting at ice cliffs and melting at supraglacial ponds (Fujita & Sakai, 2009; Han et al., 2010; Juen et al. 2014) but likely also to be little mass gain from upstream due to low flow velocities or even stagnancy reduced glacier flow from the accumulation region (Quincey et al. 2009; Schomacker, 2008; Benn et al., 2012).”

L455: Please verify wording “below Lake Merzbacher” ==> You probably mean downstream of Lake Merzbacher

Reply: Yes, It is. It was changed to “downstream of Lake Merzbacher”

L463: “... was also found ...” ==> before you wrote increasing temp and decrease in precipitation. Until 1996, not its a decrease in precipitation and decrease in temp ==> you cannot write “also” as the signals/observations are different

Reply: Thank you for your comments. “also” was deleted.

L464ff: “It is disagreement on climate ...” ==> please verify grammar

Reply: It was changed to “This is in disagreement with climate”

L474: “... space-borne datasets sources” ==> either datasets or data sources

Reply: Thank you for your suggestion. It was changed to “space-borne datasets”

L475/476: “... SIG has a velocity of about 100m/yr for large parts of the tongue ...”

==> you obviously have an internal definition of glacier tongue and glacier terminus that you do not explain before to the reader. For me the tongue would be the end of the glacier, so lowest point as would be the terminus. ==> I do not see that in Fig.3; in fact velocities at the tongue (not at Lake Merzbacher) are close to zero!

Reply: The terminus is the lowest point of the glacier (Cogley et al., 2011) tongue. But the tongue itself is the "lower, elongate part of a valley glacier or outlet glacier"(Cogley et al., 2011). Hence this included the parts with fast velocities. However, for clarification we write now "Our results show that SIG has a velocity of about 100 m a^{-1} for large parts upstream of Lake Merzbacher with a main flow direction towards Lake Merzbacher and significantly lower velocities with likely stagnant parts downstream of the lake".

L479-481: You are contradicting your own statement in the same sentence. The area in general decreased but due to the surge it increased in the same period by 2 km2 ????

Reply: It was SIG. So, It was changed to "entire SIG system "

L483-485: "The results showed that the mass balance of SIG and NIG was negative from 1975 to 2007 despite the surge of NIG." This statement somehow implies that a surge would be triggered or only be possible by previous positive mass balances or have any other positive effect on mass balance. We know that there are various mechanisms and theories on causes for surges. So reformulate this sentence.

Reply: Agreed. "despite the surge of NIG" was deleted.

L486ff: Within these 2 sentences the problem of signs becomes really obvious. I suggest to either write about mass loss all the time and keep the signs positive or talk about mass balance and keep the sign negative.

Reply: We agree although our statements were correct. We selected write now … the mass balance and the signs negative. And wrote now "For SIG, decreased mass loss in the recent decade was observed; the overall mass balance for SIG was -0.42 ± 0.09 m w.e.a^{-1} between ~1975 and 2007. For NIG, on the other hand, increased mass loss between ~1975 and 2007 could be found; a mass balance of about -0.30± 0.09 m w.e.a^{-1} was measured for all investigated time periods."

L491ff: "... elevation thinning … to be quicker ..." ==> please check wording and if expressions are appropriate

Reply: Thank you for your comments. "elevation thinning" was changed to "thinning"

Figure captions:

L722: "... tongue changes …" ==> please check expression and revise to e.g. changes in glacier front positions

Reply: The figure caption was changed to "Changes in glacier front position of SIG and NIG between ~1975 and 2007."

L724: I suppose you mean: "Mean annual flow direction and velocity of SIG in the time intervals 2002-2003 (a) and 201 to 2011 (b)." ==> because what you state reads different!

Reply: The sentence was changed to "Mean annual flow direction and velocity of SIG in the time intervals 2002- 2003 (a) and 2010-2011 (b)"

L725: See comments below and consistency in regard to labels KH9-SRTM/SPOT and time intervals

Reply: Figure and Table Captions were changed (KH-9 and SRTM, SRTM and SPOT-5, KH-9 and SPOT-5)

L734: ALOS has various sensors, so please be precise and write ALOS PRISM

Reply: It was changed to ALOS PRISM.

L736: This is the “mean annual elevation difference in the period 1975-99” NOT the annual elevation difference

Reply: It was changed to “mean annual elevation difference”

Figures:

Figure 1: This figure requires revision. The legend matches with the map frame border. The elevation range is quite strange/unique with 1526-7439. Better use round values like 1500 to 7450. It is unclear if the stretch is linear of e.g. logarithmic ==> provide interim values. There should be some buffer around the elevation scale and scale bar. Show the ASTER scene extent, when it is used – the label is unclear (also in Fig. 4). Label of SIG and Khan Tengri cannot be read.

Reply: The figure was improved. For the elevation range, the highest altitude is 7439 m (Pik Pobeda/Tomur Peak., which we included now in the figure. 2002 ASTER extend was shown in Figure 1.

Figure 2: The scale bar and north arrow need a white buffer and why grey color behind the legend?

Reply: The scale bar and north arrow were given a buffer and enlarged. The grey color behind the legend was removed.

Figure 3: Points a, b, c cannot be seen well – please change color. Similar numbers for region 1 and 2 cannot be identified.

Reply: We enlarged the points size, and change color to white. For region 1 and region 2, we added boxes. See figure 3

Figure 4: The lake dam label cannot clearly be identified. Point (e) is partly difficult to see and at different locations in the panels.

Reply: “Lake Dam” was magnified

Figure 5: Labels of points a-f cannot be read. Please magnify the labels.

Reply: Those labels were magnified.

Figure 6: Same critics for labels. Either by time consistent interval or by sensors

In general a joint layout of the figures would help and make the manuscript much nicer.

Reply: Those labels were magnified.

References:

Julia Neelmeijer, Mahdi Motagh and Hans-Ulrich Wetzel (2014): Estimating Spatial and Temporal Variability in Surface Kinematics of the Inylchek Glacier, Central Asia, using TerraSAR–X Data. Remote Sensing 6(10), 9239-9259; doi:10.3390/rs6109239, http://www.mdpi.com/2072-4292/6/10/9239

Quincey, D.J., Braun, M., Bishop, M.P., Hewitt, K.,Luckman, A. (2011): Karakoram glacier surge dynamics. Geophysical Research Letters 38(L18504), doi:10.1029/2011GL049004.

Reply：The two important references are now considered in the manuscript..

Reviewer 2

L47: decreased → decades (?)

Reply: Yes, It was changed to “decades”

L49-50: Specify what kind of “shrinkage” you mean: area, volume or mass?

Reply: It was in area. So, It was changed to “shrinkage rate in area varied”

L51: What kind of “increase” are you talking about? The percentage numbers seem to actually indicate a slight decrease in shrinkage.

Reply: Sorry. We meant “runoff increase of Aksu River”. We write now: “runoff increase of Akus River is at least partly due to increased glacier melt.””

L63: Glaciers

Reply: “Glacier” was changed to “Glaciers”

L105: measurements

Reply: It was changed to “measurements exist”

L108: What does the formula give for average precipitation then? No need to mention the formula unless you use it to something.

Reply: The formula was deleted as it was not used

L101: It’s good that you provide coordinates, but how far away are they in km?

Reply: Now, Tian Shan Station was shown in Fig. 1. It is about 120 km away from tongue of SIG.

L115: Delete “the”

Reply: “the” was deleted.

L122: Put the verbs earlier in the sentence.

Reply: It was changed to “For the KH-9 missions, the same film as for the KH-4 mission was used with a film resolution of about 85 line pairs/mm.”

L125: What does “finished-B” mean? Write out SRTM in full.

Re**ply**: It was unfilled finished Shuttle Radar Topography Mission (SRTM) data Finished-b is our mistake. It is unfilled finished SRTM.

L131: Delet either “parts of” or “entirely”

Reply: The “entirely” was deleted.

L134-135: This doesn’t make sense unless you explain why.

Reply: both glaciers were summer-accumulation type (see line 102).

L138: Write out HRG at least.

Reply: HRG was changed to “high resolution geometrical (HRG)”

L156: imagery

Reply: It was changed to “imagery”

P186: Missing punctuation after sentence.

Reply: Thank you for your comments. The “. ” Was added befor “For”.

L190: Dependent on to → On the basis of

Reply: Thank you for your comments. It was changed to “On the basis of”

L191: was set to

Reply: Thank you for your comments. “was” was changed to “was set to”

L200: Remove space

Reply: Space was removed.

L201: fields

Reply: “field” was changed to “fields”

L201: only SIG?

Reply: Yes.

L202: encompasses

Reply: It was changed to “encompasses”

L205: with → as

Reply: “with” was changed to “as”

L205: Uncertainty of what? Averaged velocities or local ones? If the latter, the uncertainty estimates seem too good.

Reply: It was average velocities. It was changed to “the final uncertainty of average velocities”

L233-237: This is a long and unclear sentence that needs to be reformulated.

Reply: This sentence was changed to “Due to the glacier surge in late 1996, outliers of NIG for the period ~1975 - 1999 and ~1975 - 2007 were defined and excluded as follows: all values larger than the sum of the maximum elevation difference (which is larger than 3σ) in the surging region, standard deviation and mean of the elevation difference.”

L242: It is not clear where the 20 m value comes from.

Reply: According to Aizen's result (1997, Journal of Glaciology, 43(145)), the precipitation at 6148 m asl. was 800 mm/yr and the thickness of annual snow-firn layers was less than 275 mm/year from 1969 to 1989 (Aizen et al., 1997). In addition, the seasonal snow depth was calculated with a maximum of 11.6 m by comparison with the SRTM C-band and SRTM X-band regulated by ICESat . Based on these findings threshold of 20 m was now introduced used in the accumulation region. This led to more realistic values (moderate elevation changes above 4,000 from 1999 to 2007 (cf. Figure 6).

L247-261: It is unclear whether these estimated penetration depths are used to correct the SRTM DEM or if they are just used to estimate the uncertainty. If the former, then this paragraph belongs in the previous section. If the latter, then why?

Reply: Penetration depths were both used to correct the SRTM DEM and to estimate the uncertainty. First, we need to get the penetration depths in each altitude. Then, correct the elevation change in each altitude. And also we got penetration uncertainty. After that, we used formula 3(per formula 2) to evaluate the uncertainty of the DEM differences.

L252: DEMs

Reply: It was changed to "DEMs"

L253: mean elevation difference within 100 m altitude zones

Reply: Thank you for your comment. It was changed to "mean elevation difference within 100m altitude zones"

L255: Delete: according to each altitude zone (100 m)

Reply: It was deleted.

L256: was discrepancy with → disagrees with the estimated

Reply: Thank you for your comments. It was changed to "Disagrees with the estimated"

L259: Need a reference for that.

Reply: This sentence was deleted.

L272: insert comma

L273: GPS points

L273: DEM's

Reply: Thank you for your comments(L272-273). We deleted the content about GPS because we used the ICESat data.

L276: How is the uncertainty estimated? As the mean absolute difference?

Reply: Yes, we got a profile with 342 samples points between 3,050 and 3,350 m a.s.l. on the glacier. And compared an absolute difference.

L277: Glacier melt can also be an elevation change. Simplify by removing sentence and adding "…, including glacier elevation changes between 2006 and 2009" to the previous one.

Reply: Thank you for your comments. The expression was changed to "included glacier elevation…"

L280-286: I immediately understood the formula, but needed to read the text 5 times before I got the point. Always use terms like "glacier-wide" or area-averaged" elevation change when you talk about spatially averaged elevation changes. Please rewrite.

Reply: The sentence was changed to "After filtering outliers caused by low image contrast (e.g by cast shadows) for optical data, radar shadow and layover for microwave data in each zone, the mean volume of each zone was used to calculate the elevation change (Formula 2).

"

L287: the mean

Reply: Thank you for your comments. It was changed to "the mean"

L288: This answers my question at L247, but it should have come earlier. It is also unclear how the correction was done. Did you apply averaged values or the actual fields in Fig. S4? And since all penetration estimates are questionable - what would be the impact on the mass balance results if the entire correction was removed? It would be good to discuss that in a few sentences somewhere.

Reply: Thank you for your comments. "Subsequently, averaged penetration depth in each altitude zone was used to correct elevation differences." was added ahead of "Considering the radar wave" close to line 270. For the impact on the mass balance after penetration correction, in section discussion 5, the following two sentences were added "Our error budget for mass balance was clearly dominated by SRTM penetration correction. The mean SRTM penetration for both SIG and NIG was 4.8 ± 1.9 m, which was larger than that in Karakorum (Gardelle et al., 2013) and in Hindu Kush (Kääb et al., 2012). The correction for radar penetration decreases the mass budgets by 0.17 m w.e. on average for the period ~1975 – 1999, and by 0.51 m w.e. on average for the period 1999 – 2007."

L289: distant?

Reply: It was changed to "Part of tongue"

L293: But table 5 has rates (dh/dt)!? I don't understand.

Reply: It was changed to "The annual average elevation change was calculated by using average elevation change divided by the time span."

L294: If there is a lack of altitude zones, then there is no continuous glacier. Do you mean lack OF DATA in altitude zones?

Reply: There is a lack of information in several altitudinal zones because there was no data in parts of accumulation region in unfilled finished SRTM and and also SPOT DEMs.

L295-299: Firstly, it is very hard to understand what you have actually done, and secondly, I don't see any justification for using (min+max)/2 in unmeasured areas. Why not just merge these altitude zones with the lower ones that have data, or simply set them to zero?

Reply: This sentence was deleted here because it duplicates L406.

Area-averaged methods were used to calculated the mass change in each zone. However, for the SPOT and unfilled finished SRTM DEMs, there was no data in several zones.Hence we need assume some scenarios (min, max, zero and (min+max)/2) to fill the altitudinal zones with data voids and to evaluate the impact on the whole mass balance. According to your suggestion, zero was also included in our test samples.

L299: dh/dt is an elevation rate, not a lowering rate (otherwise, the signs get wrong)

Reply: Yes, correct. The term was changed to “elevation rate”

L304: Uncertainty was dealt with in the last section. I would switch the two sections and move this formula there (maybe removing the need for eq. 2). Regarding Eq. 3: How can you combine elevation uncertainties (unit m) with a density uncertainty (kg m-3)?

Reply: The eq 4 was changed. And eq 4 combined elevation uncertainties with a density uncertainty. According to your suggestion, we combined the two sections in section 3.6. And the Radar penetration was in section 3.5

L318: This must be related to the deceleration of the tributaries then. The text doesn’t make any connection between the two pieces of information.

Reply: Good suggestion. This sentence was changed to “However, comparing the velocities of 2002/03 and 2010/11 shows a slight deceleration for the main stream of SIG (Supplementary Figure S6). Significant deceleration of the surface velocity were found in region 1 and region 2 (cf. Fig. 3) with high velocities (more than 60 m/a) for the period 2002/2003 and lower velocities (less than 45 m/a) for the period 2010/2011.” See line 309.

P335: Please don’t switch terms between mass loss and mass budget from one sentence to another when it involves opposite signs.

Reply: It was changed to “After 1999, a mass budget of -0.57 ± 0.46 m w.e.a-1 was measured for NIG while a mass budget -0.28 ± 0.46 m w.e.a-1 was observed for SIG. ”

L337: An elevation is not thinning. It’s the thickness that thins. Delete “elevation”.

Reply: “elevation” was deleted.

L337: Higher than what?

Reply: This sentence was changed to “We also noted that significant thinning of about 1.0 - 2.0 m a^{-1} from ~1975 to 2007 was observed close to the lake dam in the SIG (Fig. 4). ”

L340: Maybe. But in which way?

Reply: It was discussed in section 5. First, the high velocities will transport ice mass; the second, the lake enhances melt and causes calving; the last, the water likely also lubricates the glacier base bed (Quincey et al., 2009; Neelmeijer et al., 2014).

L341: Awkward wording: “analysis elevation differences measured”

Reply: It was changed to “The elevation differences measured”

L349: I would rather say ~0 considering the uncertainties.

Reply: Good suggestion. It was changed to “We also identified parts with no significant surface elevation changes at SIG above point c for ~1975 - 1999 (Fig. 4a) until ~37 km…”.

L352: Very hard to spot the number 2 in Fig. 4a, and there is no explanation in the caption to point it out.

Reply: The explanation was added in the caption of Figure 4.

L352: It’s the velocity that was faster, not your measurement. Delete “measured”.

Reply: It was changed to “where high velocities were also measured in 2002/2003 (Fig. 3a)”.

L353: Is it robust to interpret this as a surge? If the velocities were higher in 2002/03, one would rather expect thinning than thickening. You must be assuming a decelerating flow which would indeed cause thickening. But is it then a surge or a tributary stagnation? These things need to be discussed and clarified before claiming a surge. And what about zone 1? Doesn’t that look more like a fading surge considering the velocity fields?

Reply: Thank you for your suggestion. The sentence “It looks like a tributary surge.” was deleted.

L359: This is not an assumption, it’s clear.

Reply: Yes, clear evidence was derived from Landsat acquired in 1990 and 2000.

L360: Any clue when the surge happened? Satellite imagery, literature, locals etc.

Reply: The surge was reported by Maylyudov (1998) cit. in Häusler et al. 2011

L362: What is a.s.l?

Reply: Sorry, It was slip of a pen. “a.s.l.” is redundant and was therefore deleted.

L362: Move “below 4300 m a.s.l.” to the entry that says a.s.l.

Reply: Yes. It was moved.

L366: To me it looks like slight thinning throughout.

Reply: Yes, most of altitude zone except 6,300 – 6, 500.

L369: Again I don’t see a clear boundary at 4800 m a.s.l.. Very confusing.

Reply: The 4,800 m a.s.l. was deleted. This paragraph was updated because we re-evaluated the penetration depth .

L372: compared

Reply: “Compared” was changed to “compared”

L398: → the lower parts

Reply: “at parts” was changed to “at lower part”

L399: transport

Reply: It was changed.

L402: Be more specific, e.g. “…margin and enhances glacier mass loss”

Reply: Thank you for your comment. It was changed to “margin and enhances glacier mass loss.”

L404: Refer to Supplementary Fig. 2

Reply: Supplementary Fig.2 was referred.

L405: “make up the short samples” → “fill data voids”

Reply: Thank you for your comments. It was changed.

L406: See comment on L295. This just makes the paper unnecessarily complicated.

Reply: Yes, L295 duplicates L406. Hence, L295 was deleted, and L406 was kept .

L407: Delete “weight of samples”, it just makes it harder to understand.

Reply: “weight of samples” was deleted.

L408: effect → affect

Reply: It was changed.

L408: → "the area-averaged results (it adds <0.02 m a-1 of uncertainty)

Reply: It was changed to (it adds < 0.02 m a^{-1} of uncertainty)

L408: Remove figure reference.

Reply: The "Supplementary Fig.2" was deleted.

L409: Very abrupt transition to other error sources. Rewrite and start with something like "Another source of uncertainty is the variable timing of the imagery…"

Reply: Good suggestion. After we used mean annual elevation changes to tcalculate mass balance, this sentence was useless. Hence, we deleted this sentence.

L419: decreasing → decreased. You don't know if the mass loss was decreasing during 1999-2009! (you measure an average trend, not a change in trend)

Reply: Thank you for your comments. "decreasing" was changed to "decreased"

L420: showed → show

Reply: "showed" was changed to "show"

L423: More interesting – do they show decreased mass loss in 1999-2007 like your results?

Reply: Sorry, there was not continuous measurement for both glaciers.

L424: "in disagreement" or "in contrast"? Important difference. The first suggest that one of the series is in error, the second suggest different glacier conditions.

Reply: Thank you for your suggestion. The glacier size and glacier conditions were important factors to lead the mass balance differences. Here we want to talk about the tendency. Due to the recalculation of the effect of the penetration on the mass balance, the mass balance values of NIG and SIG were improved. The value is now in tendency in in line with NIG.

L429: Did you do this analysis? It certainly cannot be seen from the figure in Gardner et al. 2013.

Reply: We only got information from color type from the figure in Gardner et al. 2013. Our results also show the trend in Figure 5: increasing elevation change from point e to point g.

L431: Delete “obtained characteristics with a”

Reply: “The obtained characteristics with a” was deleted.

L433: How do you know it happened after 1990? From the Landsat image?

Reply: Yes. In Figure 2, the surging event was not observed in Landsat TM acquired in 1990, but observed in 1999.

L437: Okay, but strange order of explanation wrt. L360 and L433. This review information fits better in Section 2 as an introduction to the study sites.

Reply: Good suggestion. It was moved to the back of “between 1990 and 1999.”

L441: Are you suddenly jumping from NIG to SIG?

Reply: This paragraph was discussing about glacier surging. However, The tributary surging was somewhat farfetched. Just as the question L442, so, we deleted the sentence”Furthermore, a significant…”

L442: If you think this as a surge, then I have several requests for the paper: Fig. 5a should be expanded up the flow-line of the tributary to demonstrate the dh/dt characteristics before (1974-1999) and during/after the surge (1999-2007). This would hopefully give a much stronger support for your claim. Secondly, it raises the question whether the mass gain in this zone introduces a bias in the overall SIG mass balance since the likely thinning in the upstream areas is not captured and since the surge thickening gets extrapolated to unmeasured areas in the same altitude zones of the other tributaries. Can this explain why the 1999-2007 period is less negative than 1974-1999? You need to account for this or demonstrate that it does not impact the mass balance significantly.

Reply: as mentioned in L441, the tributary surging was deleted.

L444: Before or during?

Reply: It was during. However, this sentence was deleted.

L445: Delete. It’s obvious and how a surge is defined.

Reply: Yes, our result agrees with this opinion. So, this sentence was deleted.

L450: delete “was shown/found”

Reply: “was found” was deleted.

L453: Which way did the relationship go? Decreasing ablation with increasing thickness, I assume.

Reply: Yes. It is well known. So, we just point it out that, in general, ablation decreases with increasing debris thickness.

L458: You already said this in the previous sentence. No reason to repeat.

Reply: Agreed. “but likely also to be due to reduced glacier flow from the accumulation region ” was deleted.

L461-466: Some basic statistics would be highly appreciated. Are the trends significant?

Reply: Yes, the trends are significant. We aslo analysed the precipitation and temperature in Tian Shan Station.

L482: partially

Reply: It was changed.

L482/484: Despite? A surge is a redistribution of mass, not a change in overall mass.

Reply: “despite the surge of NIG…” was deleted.

L490: distal → lower

Reply: “distal” was changed to “lower”

L491: Delete “elevation”

Reply: “elevation” was deleted.

L492: Commas after quicker and Merzbacher

Reply: Comma was added.

Table 2: “With glacier free” → “glacier-free terrain” or “outside glaciers”. The two right columns give elevation values I believe, but it doesn’t say. Could be moved to supplement.

Reply: It was changed to “outside glaciers.” Table 3 was moved to supplementary file as S2 as suggested.

Table 3: “with GPS points to” → “between GPS points and”. Could also be moved to supplement.

Reply: Table 3 was deleted because we used ICESat GLAS

Table 5: Area-average → area-averaged. I would put the rows in order of the periods as with the columns in Table 4. Also, SIG appears first in Table 4 and last in Table 5. Please find a consistent orders for all tables and figures.

Reply: “area-average” was change to “area-averaged”. And the Table 5 was updated by using year order, (1975-1999, 1999 – 2007 and 1975 – 2007); in addition, SIG appears first.

Fig. 4: Make region 2 more visible in 4a, like done in Fig. 3.

Reply: Region 2 was made more visible in Fig. 4a..

Fig. 5: Expand 5a up along the flow line of the surging tributary. Include the years in the legend as for the other figures.

Reply: It was expanded. However, due to make figure readable, we only selected two periods. In addition, the supplementary table S3 provides all the figure 5 data.

Fig. 6: Two things don’t seem right here: 1) 1999-1974 and 2007-1999 should add up to 2007-1999 except from altitude zones with very different data coverage. 2) There appears to be a clearly increased thinning below point b for SIG in 1999-2007. This seems to agree with Fig. 4a-b, but not Fig. 5a. How can that be?

Reply: For the first question, we also noted that there was little bias (see supplementary Table S3). However, considering the uncertainties, It was still reasonable. For the second question, it also agreed with Fig.5a because below point b, the mean thinning is larger.

Fig. S1: It is misleading that both high elevations and areas without SRTM have a white color. Several high-altitude white areas do have SRTM data id one considers Fig. 4.

Reply: Good suggestion. The color was changed. The Nodata can be seen clearly.

Fig. S2: Nice figure, but I don't understand the last sentence of the caption. Is it needed?

Reply: Agreed. It is not necessary. The last sentence was deleted.

Fig. S3: VS → vs.

Reply: It was changed to "vs."

Fig. S4: Nice figure that almost deserves to be in the main manuscript. At least the debris-covered extent would be helpful for the discussion.

Reply: Thank you for your comments. This figure was changed to S5.

Fig. S5: of → between

Reply: It was changed to S2. "of" was changed to "between"

Mass changes of Southern and Northern Inylchek Glacier, Central Tian Shan, Kyrgyzstan during ~1975 and 2007 derived from remote sensing data

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Abstract

Glacier melt is an essential wellspring of freshwater for the arid regions surrounding the Tian Shan. However, the knowledge about glacier volume and mass changes over the last decades is limited. In the present study, glacier area, ~~surface elevation~~glacier dynamics, and mass changes are investigated for the period ~1975 - 2007 ~~period~~ for the Sourthern Inylchek Glacier (SIG) and the Northern Inylchek Glacier (NIG), the largest glacier in Central Tia~~e~~n Shan separated by the regularly draining Lake Merzbacher. The area of NIG increased by 2.0 ± 0.1 km^2 (~1.3%) ~~in~~ for the period ~1975 - 2007~~ period~~. In contrast, SIG has shr~~a~~unk continuously in all investigated periods since ~1975. Velocities of ~~the~~ SIG in central part of ablation region reached ~100 - 120 m/a in 2002/2003 which was slightly higher than~~.~~, the average velocity in 2010/2011 with the main flow direction ~~of SIG is~~ towards Lake Merzbacher. ~~while t~~The measured velocit~~y~~ies at the distal part of the terminus downstream of Lake Merzbacher were~~as~~ below the uncertainty, indicating very low flow with even stagnant

parts. Geodetic glacier mass balances have been calculated using multi-temporal digital elevation models from KH-9 Hexagon (1974 and 1976), SRTM3 (1999), ALOS PRISM (2006), and SPOT-5 HRG (2007). In general, a continuous mass loss for both SIG and NIG, could be observed between ~1975 and 2007. For SIG~~,~~ a mass loss of 0.43 ± 0.10 m w.e. a^{-1} and for NIG a loss of 0.25±0.10 m w.e. a^{-1} were observed for the period ~1975 - 1999. For the period 1999 – 2007, the highest mass loss of 0.57 ± 0.46 m w.e. a^{-1} was found for NIG, whilst SIG showed likely a moderate mass loss of 0.28 ± 0.46 m w.e. a^{-1}. Both glaciers slightly retreated during this period. ~~In comparison to the ~1975 - 1999 period, mass loss in the recent decade (1999 - 2007) is slightly less negative. The dominant mass loss was observed with 0.3±0.1 m w.e.a^{-1} for NIG and 0.5 ± 0.1 m w.e.a^{-1} for SIG in the ~1975 - 1999 period.~~ Between ~1975 and 1999, we identified a thickening at the front of NIG with a maximum surface elevation increase of about ~6 m a^{-1} as a consequence of a surge event. In contrast ~~S~~significant thinning (>0.5 m a^{-1}) and comparatively high velocities close to the dam of Lake Merzbacher were observed for SIG,~~Furthermore, our results~~ indicatinge that Lake Merzbacher enhances glacier mass loss. ~~glacier thinning and glacier flow was significantly influenced by Lake Merzbacher.~~

1 Introduction

Meltwater from snow and ice is an important freshwater resource for the arid regions surrounding the Tian Shan (Sorg et al., 2012). This is especially true for the Tarim Basin in Xinjiang/Northwest China whose main artery, the Tarim River, is considerably ~~nourished~~ nourished ~~(about 40%)~~ by glacial melt (Aizen et al., 2007; Sorg et al., 2012). The transboundary Asku River (named Sary-Djaz in Krygyzstan), originating in the Kyrgyz part of the Central Tian Shan and the main tributary of the Tarim River, contributes about 40% to the overall run-off of the Tarim River (Mao et al., 2004). The runoff of Aksu River has increased during the last decades (Li et al., 2008; Liu et al., 2006; Piao et al., 2012). Shen et al. (2009) estimated that 13% of the annual runoff during 1957 - 2006 in the Aksu River was due to the glaciers imbalance while Pieczonka and Bolch (2014) estimated an even higher value of ~20% for the period ~1975 - 2000. Reported shrinkage rates varied ~~between~~ up to ~3.7% for the entire Sary-Djaz Basin during 1990 - 2010 (Osmonov et al., 2013) and ~8.7% for the neighbouring Ak-Shirak Range during 1977 - 2003 (Aizen et al., 2006). Hence, the runoff increase of Aksu River is at least partly due to increased glacier melt. Changes of mass balance can be directly linked to climate change and runoff. Glacier mass balance, however, is traditionally measured in-situ. As this work is laborious and most of the glaciers are located in remote and hardly accessible terrain, measurements can only be conducted point wise for few glaciers. Several studies have shown that remote-sensing derived geodetic mass balance estimates are suitable to extend in-situ measurements in space and time (e.g. Berthier et al., 2010, Bolch et al., 2011, Gardelle et al., 2013~~, ~~; Paul and Haeberli, 2008), and it's even used to calibrate time series of in-situ glaciological records (e.g. Zemp et al., 2013).

Glaciers in Central Tian Shan experienced significant mass loss ~~in~~over the last decades. Aizen et al. (2006) determined a thinning rate of 0.69 ± 0.37 m a^{-1} (or 0.59 ± 0.31 m w.e. a^{-1} mass loss, using a density of 850 kg m^{-3} to convert volume to mass changes) for the Ak-Shyrak Massif, the second largest glacierized massif in the Central Tian Shan, while Pieczonka et al. (2013) found a mass loss of 0.42 ± 0.23 m w.e. a^{-1} using 1976 KH-9 data and the SRTM3 DEM for several~~,~~ partially debris-covered glaciers in south of Peak Pobeda/Tomür Feng (Peak Pobeda in Russian/ Tomür Feng in Chinese, it is also named after Jengish Chogsu in Kyrgyz) with a decreasing trend in the recent period (1999 - 2009).

SIG, the largest glacier in the Central ~~Tien~~ Tian Shan, is characterized by a layer of debris altering both rates and spatial patterns of melting. SIG was investigated by field based method (ablation measurements [Hagg et al., 2008]) and by remote sensing (velocity measurements [Li et al. 2013]). However, there is still a lack of volume and mass change investigations.

In the present study we used stereo 1974/1976 KH-9 Hexagon (~~F~~for ease of understanding, we unified use ~1975 KH-9~~ Hexagon~~), 2006 ALOS PRISM, and 2008 SPOT-5 High Resolution Geometrical (HRG) data and the 2000 SRTM3 DEM to assess the mass change of SIG and NIG. In addition, we investigated area changes and the glacier dynamics using Landsat TM/ETM+ and Terra ASTER imagery.

2 Study region

Inylchek Glacier is located in the~~at~~ Kumarik Catchment, the headwater of the Aksu-Tarim River Catchment~~ in the border triangle of Kyrgyzstan, Kazakhstan and China~~ between p~~P~~eak Pobeda / Tomür Feng (7,439 m a.s.l., the highest peaks of the Tian Shan) and Khan Tengri (6,995 m a.s.l.) (Fig. 1). The glacier consists of two branches: the Southern and Northern

Inylchek Glacier (SIG and NIG) which formerly had ~~formerly~~ a join~~t~~ed tongue; however, ~~but~~ glacier recession led to a separation (Lifton et al., 2014; Kotlyakov et al., 1997). The ~~area~~ space between the two tongues was filled by Merzbacher Lake as the tongue from the SIG formed an ice-barrier which dammed the meltwater (Glazirin, 2010; Häusler et al., 2011). ~~Lake Merzbacher drains almost annually in summer/autumn causing an outburst flood which can be measured up to 150 kilometres downstream with discharge peaks of up to1,500 m^3/s to 2,000 m^3/s at Xiehela hydrological station (Xinjiang/China) (Ng et al., 2007; Glazirin, 2010).~~ SIG stretches about 60.5 km in East - West ~~length~~ direction with an area of approximately~~.~~ 500 km². NIG and SIG together account for ~32% of the total glacier area of the Sary-Djaz river basin (Osmonov et al., 2013). The equilibrium line altitude **(**ELA) is located at about 4,500 m a.s.l. (Aizen et al., 2007). Existing velocity measurements of ~~the~~ SIG show surface velocities of about 100 m a^{-1} for the ~~middle~~central part of the ~~tongue~~ ablation region (Li et al., 2013; Nobakht et al., 2014) where~~. Interestingly,~~ the glacier flow is mainly directed towards Lake Merzbacher (Mayer et al., 2008; Nobakht et al., 2014).

The study region is characterized by a semi-continental climate. Precipitation recorded at Tian Shan Station (TS) (~~years~~ 1960 - 1997) (78.2°N, 41.9°E, 3,614 m a.s.l., Fig.1) and Koilu Station (K) (1960-1990) (~~70~~79.0°E, 42.2°N, 2,800 m a.s.l., Fig.1) was 279 mm a^{-1} and 311 mm a^{-1}, respectively (Reyers et al., 2013) with about 75% of precipitation occurring during summer (May - September). Hence, both SIG and NIG receive a significant amount of the accumulation during summer as compar~~able~~ed to Himalayan Glaciers (Osmonov et al., 2013). No long-term precipitation measurements exist~~s~~ on the glacier itself. However, a correlation between annual accumulation measured by stakes at 6,148 m a.s.l.~~(A_k)~~ and annual precipitation ~~(P)~~ was constructed ~~to~~for Tian Shan Station ~~, which was $A_k = 27.7 \cdot P^{0.61}$~~ (Aizen et al., 1997). The mean annual temperature at Tian Shan Station is about -7.7 ℃ with January being the coldest month (-21.8 ℃) and July the warmest (4.3 ℃) (Osmonov et al., 2013).

23 Data and Methods

2.13.1 Remote sensing datasets

Declassified Hexagon KH-9 Hexagon, SPOT-5 HRG, ALOS PRSIM, Terra ASTER, Landsat TM/ETM+ and SRTM3 data were used to obtain information about the surface elevation, surface velocity and area extent of both SIG and NIG for different periods (Tab. 1).

The KH-9 Hexagon mission was part of the US Keyhole reconnaissance satellite program whose images were declassified in 2002 (Phil, 2013). The employed frame camera system was used on a total of 12 missions between 1973 and 1980. Each scene is characterized by a spatial resolution of about 20 - 30 feet (6 - 9 m) with 240 x 120 km^2 ground coverage (Surazakov et al., 2010; Pieczonka et al., 2013). For the KH-9 missions the same film as for the KH-4 mission with a film resolution of about 85 line pairs/mm was used. The film resolution is about 85 line pairs/mm. In our study, we used Hexagon images from mission 1209 flown in November 1974 and mission 1,211 flown in January 1976.

For the period around 2000, the unfilled finished Shuttle Radar Topography Mission (SRTM) data with 3 arc-second resolution (approximately 90-meter) (USGS, 2006) was used. Yang et al. (2011) and Shortridge et al. (2011) reported an absolute vertical accuracy of the final SRTM3 DEM of about 10 m. However, the accuracy in mountainous terrain is likely worse (Gorokhovich et al., 2006; Pieczonka et al., 2011; Surazakov et al., 2006). The original SRTM3 dataset has some data voids especially at high and steep elevation -regions due to radar shadow and layover effects (Supplementary Figure S1). Thus, parts of the accumulation regions are not entirely covered by the SRTM3 DEM. However, tThese gaps have been filled in the SRTM3 CGIAR version 4 DEM using auxiliary data (Jarvis et al., 2008), but the exact time is only known for the original data. The void filled SRTM3 DEM was used for the orthorectification of ASTER images and the calculation of the glacier hypsometry (Supplementary Figure S2). Due to the acquisition in February 2000 the DEM represents the glacier surface as constituted at the end of the 1999 ablation period. However, the penetration of the C-band radar waves of about 1 - 2 m on exposed ice and up to 10 m on dry, cold firn (Gardelle et al., 2012; Rignot et al., 2001) needs to be taken into account.

The SPOT-5 HRG instruments offer across-track stereo images with the viewing angle being adjustable through ±27° from two different orbits, which are suitable for DEM generation in high mountain areas (Toutin, 2006). Due to the precise on board measurements of satellite positions and attitudes of the SPOT-5 orbit, each pixel in a SPOT-5 image can be located on the ground with an accuracy of ±25 m on the 66% confidence level without additional ground control points (GCPs) (Berthier et al., 2007; Bouillon et al., 2006). ~~The SPOT-5 HRG images are suitable for DEM generation in high mountain areas (Toutin, 2006).~~ Two SPOT-5 HRG images, acquired on 5 Feb. 2008 with an incidence angle of -9.79° and 24.94° offering a Base to Height Ratio (B/H) of about 0.63, were used for DEM generation (Tab. 1). The image contrast on the glacier of the utilized images is suitable for DEM generation, but several regions in the SPOT-5 DEM are influenced by cast shadows and were eliminated from the final DEM (~~see Fig. 4 &~~ Supplementary Figure S2).

ALOS was launched in January 2006, carrying the PRISM optical sensor in a triplet mode, i.e. in forward, nadir and backward views in along-track direction (Takaku et al., 2004). We used the nadir and backward images ~~with B/H-ratio 0.5~~ (Tab. 1). The horizontal accuracy of the geometrical model with Rational Polynomial Coefficients (RPC) (which contains ~~information about~~ the interior and exterior information) can achieve an accuracy of better than 6.0 m (or 7.5 m in horizontal direction and 2.5 m in vertical direction) without any GCPs (Takaku et al., 2004; Uchiyama et al., 2008). This accuracy can be improved by using additional GCPs.

In addition to the above mentioned image~~ries~~ we used Landsat TM/ETM+ and Terra ASTER data to investigate the changes in glacier extent and to observe the glacier flow (Tab. 1). Unfortunately only SIG was covered by the utilized ASTER scenes.

~~2.2~~3.2 Glacier boundary

The glacier boundaries were manually delineated from Landsat TM/ETM+, orthorectified panchromatic ~~as both~~ SPOT-5 and KH-9 images. Debris cover on the tongue of SIG hampered the accurate identification of the glacier margin. However, water outlets at the front of SIG and traces left after the river flow around the tongue are visible in the images. We identified the lines of the traces surrounding the debris covered ice as the glacier terminus boundary (Fig. 2a). For the NIG terminus boundary the delineation between the water and debris was used as the terminus boundary of ice (Fig. 2b). Furthermore, the hillshade based on the SRTM3 DEM provided additional information to detect the glacier boundary. The accuracy of the glacier outlines is strongly influenced by debris cover and different spatial resolutions of the used satellite datasets (Paul et al., 2013). We estimated the uncertainty using a buffer of 10 m for the KH-9 images and half a pixel for Landsat TM/ETM+ images in bare ice region and good snow conditions (cf. Bolch et al., 2010). For the debris-covered partsregion, a buffer of 2 pixels of each images was used to evaluate the delineation uncertainty. We assume that the uncertainty due to image co-registration is captured with the buffer method. his led to an uncertainty of the mapped NIG area of 2.7%, 1.8%, 1.3%, 0.5% and SIG area of 1.9%, 1.3%, 0.9%, and 0.3% for the Landsat TM, KH-9, Landsat ETM+ and SPOT5 images. Under consideration of the law of error propagation, the final uncertainty θ_{change} was calculated using equation 1.

$$\theta_{change} = \sqrt{\theta^2_{period1} + \theta^2_{period2}} \quad (1)$$

Where $\theta_{period1}$, $\theta_{period2}$ represent the uncertainties of the glacier outlines in period1, and period2. The mapping uncertainties -vary are between 0.3 - 3.7% (Tab. 2).

2.33.3 Flow velocity of SIG

To investigate the dynamic behaviour of the SIG, we measured glacier displacementvelocity rates using multi-temporal optical satellite imagery covering a time span of about one year. A frequency based feature tracking (phase correlation) was performed using the EXELIS VIS ENVI add-on COSI-Corr in order to get the horizontal offset of corresponding image points. The tracking was performed using the method of phase correlation. For ASTER data a previous subpixel-coregistration was performed as described in Leprince et al. (2007) using the gap-filled SRTM3 CGIAR DEM, which was bilinearly resampled to 30 m, as vertical reference. Landsat level 1T data were assumed to be quasi-coregistered because of the same sets of GCPs and vertical references used for orthorectification. On the basis ofDependent on to an expected annual average velocity of SIG of up to 90 m/a (observed in 2003/2004 [Mayer et al., 2008]) and the images' resolution, the step size was set to four pixels for ASTER and two pixels for Landsat. Hence, both displacement maps have a final resolution of 60 m.

The relative offsets of the co-registered images show the phase difference of the previously Fourier transformed input data and can be estimated by the correlation maximum (Leprince et al., 2007). For the 2010/2011 observation period, offsets in the north-south- and east-west -direction were measured with an accuracy of 1/7 pixel using quasi coregistered Landsat TM (L1T) data. For the 2002/2003 period, we achieved a precision of 1/4 pixel based on 1/25 pixel-coregistered ASTER (L1A) data. A Signal-to-Noise Ratio (SNR) of 0.9 was selected and applied to filter obvious outlierserrors. The reliability of the displacement vectors was assessed by the ratio of the RMSE and the resolution of the respective input data. Beside SIG ,

~~velocity field were also derived for adjacent glaciers. The calculation of the RMSE values takes SIG observations into account. Therefore, the survey compasses a huge amount of significant and non-significant velocity measurements, which allows a solid reliability assessment. Beforehand, e~~Errors caused by clouds, topography and low image contrast have been removed from the matching result. The final uncertainty has been determined to be 3.5 m/a for 2002/2003 and 4.7 m/a for 2010/2011.

~~2.4~~3.4 DEM generation and DEM post processing

KH-9, ALOS PRISM and ~~the~~ SPOT-5 HRG data were processed by using ~~the~~ Leica Photogrammetry Suite (LPS), vers. 2013 with the reference system UTM WGS84 Zone 44.

For the stereo processing of the KH-9 images, we measured 38 GCPs for the DEM covering the lower part of Inylchek Glacier and 47 GCPs for the stereo pair covering the accumulation region of Inylchek Glacier with a final RMSE of ~1 m. GCPs coordinates and elevations were derived from Landsat 7 ETM+ scenes and the SRTM3 DEM. For the processing, the frame camera model in LPS, was used and the final resolution of the KH-9 DEMs was 25 m.

ALOS PRISM and SPOT-5 were processed with four additional GCPs in order to improve the accuracy of the exterior orientation (Supplementary Table S1). The automatically generated tie points (TPs) were visually checked in terms of ground objective and topographic features. In total, 120 TPs were used. The spatial resolution of the ALOS and SPOT-5 DEMs was 10 m. Differencing of multi-temporal DEMs necessitates a co-registration including the removal of horizontal and vertical offsets (Pieczonka et al., 2013). We used the analytical method proposed by Nuth and Kääb (2011) which has been proven to provide robust results and to be computationally effective (Paul et al. 2014). All DEMs were bilinearly resampled to the same cell size of 30 m. The resolution is a compromise between the possible higher resolution of KH-9 and SPOT-5 DEMs and the lower resolution of the SRTM DEM. The shift vectors were calculated based on selected ice free sample regions (Supplementary Figure S3). The resulting horizontal shifts were in the order of 2 pixels and the z-offsets varied between 1.3 m and almost 20 m (Supplementary Table S2~~see Table 2~~).

~~2.5~~3.5 Radar Penetration

Radar penetration for the SRTM C-band in ice, firn and snow needs to be considered (Gardelle et al., 2012; Kääb et al., ~~-~~2012; Mätzler and Wiesmann, 1999). A Landsat ETM+

(Level 1) scene from 18 February, which is within the time of the SRTM mission (11 - 20 February 2000) revealed that SIG and NIG were covered by snow. We used available ICESat GLA14 footprints to compare with SRTM3 elevation data in order to assess the penetration depth as described by Kääb et al. (2012). Six out of nine ICESat tracks covering both SIG and NIG from 2003 to 2004 were selected. We classified those footprints into glacier free terrain, debris-covered regions (region a and region b), bare ice and accumulation regions (Supplementary Figure S4). Fortunately, there was an excellent track over 4,300 m a.s.l.. We eliminated the differences of the elevation change between 2000 and 2003/2004 by using the elevation change rate between the footprints acquired in 2003 and 2004. The results show a mean penetration depth of -0.1 ± 3.2 m for the glacier free terrain, 1.3 ± 2.9 m for the debris-covered region a, -3.6 ± 4.5 m for the debris-covered region b (3,500 - 3,600 m a.s.l.) where some parts are bare ice, -4.3 ± 2.3 m for bare ice parts in altitudes from 4,000 to 4,300 m a.s.l. and -6.8 ± 2.1 m for the bare ice parts in altitudes from 4,300 to 5,100 m a.s.l. There was no data higher than 5,100 m a.s.l.. Furthermore, we compared the SRTM C-band and SRTM X-band DEMs to estimate the radar penetration based on ICESat footprints (cf. Gardelle et al., 2012) though 6 - 16 m penetration depth was reported at 10.7 GHz (SRTM X-band had 10GHz) (Surdyk, 2002). Both DEMs were resampled to 30 m resolution. The result show~~ed~~ that the mean elevation difference within 100 m altitude zones varies between 1.7 m in the lower debris-free ablation area and about 2.1- 4.2 m for altitude within 4,000 - 5,100 m a.s.l. ~~In the latter altitude~~ the penetration depth of both lower debris-free ablation region and altitude with 4,000 - 5,100 m a.s.l. was 2.2 - 2.6 m lower as the depth revealed by comparing ICESat GLA to SRTM3 data. The maximum elevation difference was about 9 m between SRTM C-band and SRTM X-band DEMs (Supplementary Figure S5), which ~~was~~ disagrees ~~discrepancy~~ with the estimated penetration (9 m at 4,500 m a.s.l.) in Akshiirak massif by using a linear method (cf. Surazakov et al., 2006). The uncertainty of the radar penetration (*erp*) was estimated by the Standard Deviation (STD) to be 1.9 m. Consequently, the penetration depth was evaluated by using sum of the difference between SRTM C-band and SRTM X-band DEMs and 2.6 m. ~~It was assumed that the possible slight penetration of the x-band radar beam is within this uncertainty range.~~ Subsequently, averaged penetration depth in each altitude zone was used to correct elevation differences.

~~In order to validate the accuracy of the DEMs, we randomly collected six Differential GPS points measured with Uni-Strong GPS-RTK in 2010. Among the GPS points, three were~~

~~located on the debris covered glacier part, two were located on ice-free terrain and one was on the glacier surface (Table 3). The mean difference between GPS and SPOT-5 DEM was -8.2 m with a standard deviation of 6.6 m before co-registration. After co-registration of SPOT-5 DEM with SRTM3 (master DEM), the mean offset was -0.4 m with a standard deviation of 5.7 m. However, we cannot evaluate the bias of ablation in the debris covered region and the glacierized region between 2008 and 2010 and we also cannot evaluate the bias from the points by GPS in comparison to the DEMs cell size. In order to analyse the relative uncertainty of the ALOS DEM compared to the SPOT-5 DEM we additionally measured a profile with 342 sample points between 3,050 and 3,350 m a.s.l. on the glacier. The results showed that the uncertainty is 4.5 m with a standard deviation of 3.6 m. This uncertainty included the glacier melt and glacier elevation changes between 2006 and 2007.~~

~~2.6~~3.6 Glacier elevation change and mass balance

The elevation change was calculated based on the area-averaged value per 100 m elevation zone from DEM differencing (cf. Gardner et al., 2013; Xu et al., 2013; Formula 2, Supplementary Figure S2). After filtering outliers caused by low image contrast (e.g by cast shadows) for optical data, radar shadow and layover for microwave data in each zone, ~~Data voids typically caused by low image contrast (e.g by cast shadows) for optical data, radar shadow and layover for microwave data, and as a consequence of outlier filtering, there are missing values in each zone. Thus,~~ the mean volume of each zone was ~~be~~ used to calculate the elevation change (Formula 2).

$$\Delta h_{gl} = \frac{\sum_{i=1}^{n} \Delta h_i * s_i}{s_{all\ \ zones}}$$

(~~3~~2)

where i is the number of zones, Δh_i is the mean glacier elevation change in the respective zone after radar penetration correction, s_i is the area of each zone, n is the total number of zones, and $s_{all\ zones}$ is the total area of all zones. The distal part of the tongue of SIG, which is not covered by the SPOT-5 DEM (Fig. 1), was filled with the ALOS DEM. In order to account for the different times of image acquisition of ALOS PRISM and SPOT-5 we used the elevation change per year for ~~gap-~~filling the gaps of SPOT-5 DEM. ~~Where there was a lack of altitude zones (zones of 6,800 - 7,100 in SIG and 6,500 - 6,700 in NIG), we have used the maximum elevation change, minimum elevation change and an half of minimum and maximum elevation change to interpolate that lack according toFigure 6.~~ ~~However, there are~~

few weights of area for those regions (cf. supplementary figure 2), it is not sensitive for calculating mass balance by using Area-average mass balance and could be omitted. A density of 850 ± 60 kg m^{-3} was used to convert the volume to actual mass change (cf. Huss, 2013).

The accuracies of the final DEM differences were evaluated with regard to the vertical offset over ice-free terrain which is supposed to be stable. Outlier values for the 1999 - 2007 periods were identified by 3σ and excluded from further processing (cf. Gardelle et al., 2013; Gardner et al., 2013). Due to the glacier surge in late 1996, outliers of NIG for the period ~1975 - 1999 and ~1975 - 2007 were defined and excluded as follows: all values larger than the sum of the maximum elevation difference (which is larger than 3σ) in the surging region, standard deviation and mean of the elevation difference. After outlier cleaning several obvious errors could still be detected in the accumulation regions. According to the annual snow-firn layers (the thickness was less than 275 mm/year) at 6,148 m a.s.l. on SIG from 1969 to 1989 (Aizen et al., 1997), the maximum accumulation can be inferred to be less than 9.1 m (275 mm/year * 33 years) for the period ~1975 - 2007. The maximum seasonal snow depth in February 2000 was estimated calculated to bewith 9.0 m by comparingison with the SRTM C-band and SRTM X-band (cf. section 3.5)(See below). Hence, we considered In this case, a threshold of 20 m (including 2.6 m underestimated) as the maximum accumulation was used for elevations above 4,000 m a.s.l.. In order to analyse the relative uncertainty of the ALOS DEM compared to the SPOT-5 DEM we additionally measured a profile with 342 sample points between 3,050 and 3,350 m a.s.l. on the glacier. The results revealed anshowed that the uncertainty ofis 4.5 m with a standard deviation of 3.6 m. This uncertainty from ALOS DEM included glacier elevation changes between 2006 and 2007.

The uncertainty of the differences of the different DEMs was estimated by the normalized median absolute deviation (NMAD) (which was expressed by $1.4826 * MED(|\tilde{x} - x_i|)$, x_i: elevation difference; $\tilde{x}$:Median) in for the ice free terrain (Supplementary Table S2see Table 3). Considering the radar wave penetration accuracy of 2.3 m, the uncertainty of the DEM differences was calculated according to equation 23. The biases of different DEMs in stable and non-glacierized regions after co-registration are shown in Supplementary Table S2. The final mass balance uncertainty (E) has been calculated considering the DEM uncertainty (e) where t is the observation period, ice density (ρ_I: 850 kg/m^3) the snow/ice density uncertainty ($\Delta\rho$: 60 kg/m^3), and the water density (ρ_w: 999.92 kg/m^3) (Equation 4).

$$e = \sqrt{NMAD^2 + 2.3^2} \quad (3)$$

$$E = \frac{e\sqrt{(\Delta\rho)^2 + (\rho_I)^2}}{t * \rho_w} \quad (4)$$

~~3~~4 Results

~~3.1~~4.1 Glacier flow

We noticed high velocities with an average flow of about ~100 - 120 m/a (between point b and point c representing the central ablation region) for SIG towards Lake Merzbacher while the remaining part of the debris-covered tongue (between point a and point b, lower ablation region/downstream of Lake Merzbacher) has significantly lower velocities with decreasing rates ~~has~~ and likely stagnant parts at the terminus (Fig. 3). An obvious low flow section (less than 30 m/a) at point b, upstream of the turn to Lake Merzbacher was observed in both 2002/2003 and 2010/2011 (Fig. 3). A significant acceleration was observed from point b to the lake dam. These results are in agreement with Nobakht et al. (2014).

Most tributaries have active flows until the confluence of the glacier with velocities varying typically between 30 and 60 m/a. The general patterns and velocities in main flow direction are similar for both investigated periods (2002/2003 and 2010/2011). However, comparing the velocities of 2002/03 and 2010/11 shows a slight deceleration for the main stream of SIG (Supplementary Figure S6). Significant deceleration of the surface velocity were found in region 1 and region 2 (cf. Fig. 3) with high velocities (more than 60 m/a) for the period 2002/2003 and lower velocities (less than 45 m/a) for the period 2010/2011. ~~Hence, the main flow direction of the tongue is towards Lake Merzbacher and not to the end of the glacier tongue. Most tributaries have active flows until the confluence of the glacier with velocities varying typically between 30 and 60 m/a. The general patterns and velocities in main flow direction are similar for both investigated periods (2002/03 and 2010/11). However, there are discrepancies in region 1 and region 2 where we found high velocities for the period 2002/03 and lower velocities for the 2010/11 period (Fig. 3). Comparing the velocities of 2002/03 and 2010/11 shows a slight decrease for the main stream of SIG (Supplementary Figure S5).~~

~~3.2~~4.2 Glacier area change

SIG shrank continuously by about 0.1 ± 0.1 km^2 (0.007 ± 0.007 km^2 a^{-1}), 0.5±0.1 km^2 (0.056 ± 0.011 km^2 a^{-1}) and 0.2 ± 0.1 km^2 (0.025 ± 0.013 km^2 a^{-1}) during the periods ~1975 - 1990, 1990 - 1999, and 1999 - 2007. The overall area loss of SIG was 0.8 ± 0.1 km^2 (0.025 ± 0.003 km^2 a^{-1}) during ~1975 and 2007, accounting for ~0.2% of its area in ~1975. NIG lost an area of 1.2 ± 0.1 km^2 (0.08 ± 0.007 km^2 a^{-1}) during the period ~1975 - 1990 followed by an area increase of 3.7 ± 0.1 km^2 (0.411 ± 0.011 km^2 a^{-1}) during the period 1990 - 1999~~)~~. Within this period, the glacier showed a strong advance of about 3.5 km. The glacier shrank again by 0.4 ± 0.1 km^2 (0.050 ± 0.013 km^2 a^{-1}) in the consecutive period (1999 - 2007). Overall, the area of the NIG increased by 2.0 ± 0.1 km^2 (0.063 ± 0.003 km^2 a^{-1}) during ~1975 - 2007, accounting for ~1.3% of its area in ~1975 (Fig. 2; Tab. ~~4~~3). Consequently, the area of the entire Inylchek Glacier system increased by 1.3 ± 0.1 km^2 (~0.2%) between ~1975 and 2007.

~~3.3~~4.3 Glacier mass change

The mass budget of SIG and NIG was -0.43 ± 0.10 m w.e. a^{-1} and -0.25 ± 0.10 m w.e. a^{-1}, respectively for the ~1975 - 1999 period, after 1999, a mass budget of -0.57 ± 0.46 m w.e. a^{-1} was measured for NIG while a mass budget -0.28 ± 0.46 m w.e. a^{-1} was observed for SIG. Both SIG and NIG experience a mass loss (0.42 ± 0.11 m w.e. a^{-1} and 0.30 ± 0.11 m w.e. a^{-1}) between ~1975 and 2007 (Fig. 4~~c~~ & Tab. 54). We also noted ~~that~~ significant thinning of about 0.5 - 2.0 m a^{-1} from ~1975 to 2007 for SIG ~~was observed~~ close to the lake dam~~the elevation thinning at the dam in the SIG was higher (1.0 - 2.0 m a^{-1} from ~1975 to 2007)~~ (Fig. 4). At this location, -high flow velocities were observed (Figure 3), which causes more ice to be transported there (Ng et al., 2007; Mayer et al., 2008). ~~Thus, the significant elevation thinning of this part could be related to Lake Merzbacher.~~

The ~~analysis~~ elevation differences measured along the main flow line allows more detailed insights into the characteristics of the glaciers behaviour (Fig. 5). ~~For the~~ SIG showed a surface lowering from its terminus to point b for the periods ~1975 - 1999 and 1999 - 2007 (Fig. 5). There are mean large variation in elevation changes ~~amplitudes in elevation change~~ between point a and b below Lake Merzbacher (Fig. 5) where the glacier is ~~be~~ heavily debris covered and shows -low or even no surface flow (Fig. 3). A clear surface lowering could be observed upwards the glacier, bBetween point b and c g for all investigated the periods (Fig. 4 and Fig. 5). -We also identified that parts with no significant surfaceof the elevation changes at SIG above point c for 1999 ~1975 - 2007 1999 (Fig. 4a) until ~37 km from the terminus (Fig. 5 SIG). An apparent elevation increase at a mean rate of 1 - 2 m a^{-1} was observed for the period 1999 - 2007 in region 2 (above point g) of the accumulation region infor SIG (Fig. 4a4b) where decreased velocities were also faster measured in for the period 2002/ - 2003 and 2011 - 2012 (Fig. 3a). It looks like a tributary surge. In contrast, NIG showed largea significanta clear thickening with maximum values of ~6 m a^{-1} at close to the terminus around (point d) for the period ~1975 - 1999 while the glacier a rapidly thinned at a rate of thinning of ~4 m a^{-1} further upwards the glacier tongue was measured (between point e and f; Fig. 5 NIG). Hence, a large amount of mass was transferred from the accumulation to the ablation region which is a typical sign for a glacier surge.. In contrast, NIG showed a clear thinning throughout the tongue after 1999.

SIG experienced thinning throughout all altitude zones except at elevations between 6,300 and 6,500 a.s.l. for the period ~1975 - 1999. The most obvious thinning was observed at 3,700 - 4,500 and 5,400 - 5,800 m a.s.l.. For the period 1999 - 2007 period, sSurface lowering -was measured only below 4,500 m a.s.l. with a mean rate of about 0.7 9 ± 0.5 m a^{-1} below 4,300 m a.s.l.. In contrast a Meanwhile, clear thickening with a mean rate of about 0.2 ± 0.5 m a^{-1} ,was observed above between 4,5300 – 4,900 m a.s.l. with a mean rate of about 0.16 2 ± 0.5 m a^{-1}. (Fig. 6; Supplementary Table S3). For the entire investigation period (~1975 – 2007), the surface elevation of the SIG decreased below 6,500 m a.s.l.. It indicated that the surface thickening between zones 4,300 and 4,800 for period 1999 - 2007 is small and cannot offset the surface thinning for period ~1975 - 1999. NIG showed a different behaviour in more or less all altitudes which can be explained by due to its surge-type . However, Compared to elevation changes in the same altitude of SIG for the 1999 - 2007 period, NIG experienced higher mass loss between e 3,300 - 3,600 m a.s.l. (2.0 ± 0.5 m a^{-1}) than SIG (.± 0.5 m a^{-1}). Consequently, the stronger thinning at the tongue in comparison to SIG could be due to the quiescent phase after the surge.

45 Discussion

~~4.1~~5.1 ~~5.1~~ Uncertainty

Seasonal snow in the accumulation region and debris cover, as also present in our study region, typically complicated precise glacier mapping (cf. Bolch et al., 2010, Paul et al., 2013). In order to assess our uncertainty estimate, ~~evaluated by using buffer method was~~we compared the results of the buffer method used with the approach suggested by Pfeffer et al (2014). The results show that ~~-~~the delineation uncertainty of SIG~~-~~ using~~ the~~ their approach with 30 m from Landsat TM ~~(30 m resolution)~~ was about 9 km^2, which is smaller than our results of about 11 km^2. Hence we think our approach provides a reliable uncertainty estimate especially as we used a larger buffer of ~~xxx m~~2 pixels in each images for the debris-covered parts.

One critical issue with all studies using the SRTM3 DEM for geodetic mass balance calculations is the unknown C-band radar penetration into snow and ice. We estimated the penetration using ICESat laser altimetry data which is one of the ~~the~~ most robust methods in case field data is not available (Kääb et al., 2012). The uncertainty for our mass balance estimation is also ~~-~~strongly influences by the penetration correction. The estimated mean SRTM -penetration for both SIG and NIG was 4.8 ± 1.9 m.~~,~~ This is larger than the correction estimated for the ~~an that in~~ Karakorum (Gardelle et al., 2013) and ~~in~~Hindu Kush (Kääb et al., 2012). The correction for radar penetration decreases the mass budgets on average by 0.17 m w.e. for the period ~ 1975 - 1999 and by 0.51 m w.e. for the period 1999 - 2007.

One of the further major uncertainties in our study is caused by the lack of information in several altitudinal zones due to data voids in the accumulation regions (Supplementary Figure 2). Pieczonka et al. (2013) used different suitable assumptions to fill the data voids in accumulation regions. In this study, the maximum, minimum and mean elevation changes observed in the accumulation regions were used to fill the voids and to evaluate the impact on the whole glacier mass balance. We found that the area in those zones were too small (0.5% above 6,500 m a.s.l. in area) to affect the results significantly. The different assumptions led to a variation of the mass balance by only < 0.02 m a^{-1}. This number was added in to the uncertainty terms.~~ of uncertainty (include exact dates) addition, we did not consider the seasonal correction because those DEMs are from winte~~

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~~4.2~~5.2 Glacier changes

Our study revealed only a slight retreat of SIG during ~1975 and 2007 while a strong advance for NIG could be identified between 1990 and 2000. Osmonov et al. (2013) reported an average shrinkage of 3.7 ± 2.7% from 1990 to 2010 with 10 advancing glaciers in the upper Aksu Catchment. Our results tend to be in agreement with Osmonov et al. (2013) who, however, did not analyse SIG and NIG separately and did not report the NIG surge. Glacier shrinkage in adjacent regions such as in Northern Tian Shan (Bolch, 2007; Aizen et al., 2006), or eastern/Chinese part of Tian Shan (Ding et al., 2006), was significantly larger. ~~The glacier retreat in adjacent regions varied between 3.3% in Aksu River (China) and ~30% in valleys of Zailiyskiy and Kungey Alatau during the last decades (Bolch, 2007; Aizen et al., 2006; Liu et al., 2006) with highest shrinkage rates in the outer and more humid ranges and the lowest in the inner and drier ranges (Sorg et al. 2012 Narama et al. 2010). In western China, including the Chinese part of the Tian Shan, more than 80% of the glaciers were retreating and only some glaciers are in an advancing phase for the period 1965 to 2001 (Ding et al., 2006).~~

Our observed velocities for SIG (~120 m a^{-1} for the main tongue) are in agreement with Nobakht et al. (2014) and Neelmeijer et al. (2014) who measured velocities rate~~values~~ of 0.3 - 0.4 m day^{-1} (~100 - 150 m a^{-1}) based on ASTER and Landsat data, but larger than the 0.2 m day^{-1} (~75 m a^{-1}) noted by Li et al.~~,~~ (2013) based on ALOS PALSAR data. The velocity close to Lake Merzbacher between 2002 and 2003 (75 - 90 m a^{-1}) is also in agreement with in-situ measurements (80 - 90 m a^{-1}, Mayer et al., 2008). Glacier calving could be observed for the SIG with mean velocities of up to 0.4 m day^{-1} between 2009 and 2010 (Nobakht et al., 2014). Furthermore, the elevation changes were ~~a huge mass loss~~about -2.0 - -0.5 m a^{-1} ~~in~~ for the periods ~1975 - 1999 and 1999 - 2007 near the lake dam. Flow velocities at the ~~middle part~~central ablation region of SIG ~~tongue~~ (between point b and point c) were higher than ~~at parts~~ at the tongue below Lake Merzbacher (between point~~s~~ a and point b, Fig. 3). High velocities transport~~s~~ mass from upstream and offset the mass loss due to ice melt. Furthermore, ~~the lake enhances melt and causes calving. T~~the water probably~~likely~~ also lubricates the glacier ~~base~~ bed (Quincey et al., 2009; Neelmeijer et al., 2014). Hence, the lake~~s~~ likely causes the high velocity until the lake margin and enhances glacier mass loss~~influences the ice dynamics~~ (cf. Mayer et al. 2008)~~and the mass change of a glacier~~.

Geodetic mass balance measurements of 12 mainly debris-covered glaciers south of Pik Pobeda/Tomur Peak close to our study area revealed that most of the glaciers have been losing mass with rates between 0.08 ± 0.15 m w.e. a^{-1} and 0.80 ± 0.15 m w.e. a^{-1} for the time period 1976 - 2009 (Pieczonka et al., 2013) and two glaciers gained mass and one glacier (Qingbingtan Glacier No.74) showed signs of a surge similar to NIG. The mass loss was lower during the last decade (1999 - 2009) than before ~1975 1999 (Pieczonka et al., 2013). This tendency is in line with our results for both SIG and NIG where we found on average a clear mass loss during 1975 - 1999 followed by a decreasing decreased mass loss between 1999 and 2007, but it is a little difference for NIG which showed surge-type behaviour. Existing in-situ mass balance measurements in the Tian Shan also showed clearly negative mass budgets since the beginning of the measurements in the 1960s (WGMS 2013; Sorg et al. 2012). The mass balance from Kara bBatkak and Tuyuksu glaciers, for instance, was -0.77 mm w.e. a^{-1} and -0.59 m w.e. a^{-1} from between 1974 –and 1990, respectively and the mass balance of Tuyuksu Glacier was -0.35 m w.e. a^{-1} from 1999 to 2007 (Unger-Shayesteh et al., 2013; WGMS, 2013; Cao, 1998). The tendency of Tuyuksu Glacier mass balance in the recent period is in line with the observed mass loss for SIG for which we found an average mass loss about -0.43 ± 0.10 m w.e. a^{-1} during ~1975 - 1999 followed by mass loss of -0.28 ± 0.46 m w.e. a^{-1} during 1999 -2007. However, the mass balance of the Urumqi Glacier No.1 was -0.24 m w.e.a^{-1} during 1975 - 1999, and -0.63 m w.e. a^{-1} during 1999 - 2007 (Wang et al., 2012; WGMS, 2013). This tendency is in line with our results for NIG for which found on average a mass loss (-0.25 ± 0.10 m w.e. a^{-1}) during ~1975 - 1999 followed by an accelerating mass loss (-0.57 ± 0.46 m w.e. a^{-1}) during 1999 -2007 although both glaciers are very different in size and characterisitcs. Further studies based on ICESat laser altimetry pointed out that, on average, glaciers in the Tian Shan underwent clear mass loss between 2003 - 2009 (-0.58 ± 0.21 m w.e. a^{-1}) (Gardner et al., 2013). The mass loss of Gardner et al. was a slightly higher than SIG, but similar with NIG. Furthermore, the elevation change for SIG is more pronounced in lower altitude of SIG is less than in higher altitudes regions as seen from the two ICESat profiles. Comparison with our result, it is different in this region.

The obtained characteristics with a clear thickening at the tongue of NIG and a lowering in higher altitudes (Fig. 5) together with the data of area and length change are a clear indicator for a surge event that happened between 1990 and 1999. The surge event of the NIG probably happened in late 1996 with an advance of about two kilometres (Maylyudov (1998) cit. in Häusler et al. 2011). Surging glaciers in the Tian Shan were also reported by Narama et al. (2010), Osmonov et al. (2013), Pieczonka et al. (2013), Pieczonka and Bolch (2014) and, in earlier times by Dolgoushin and Osipova (1975),). hence this phenomenon is also not

~~infrequent in the Tian Shan. The surge event of the NIG probably happened in late 1996 with an advance of about two kilometres (Maylyudov (1998) cit. in Häusler et al. 2011).~~ However, NIG surging ~~it~~ was a non-typical surging event due to the lack of surge characteristics such as: areas of stretched ogives, erosion scars, transverse crevasses or breaching structures; Hodkins et al. (2009) described this phenomenon as partial surges. NIG showed a different behaviour in more or less all altitudes which can be explained by due to its surge-type. However, compared to elevation changes in the same altitude of SIG for the period 1999 - 2007, NIG experienced higher thinning between elevation 3,300 - 3,600 m a.s.l. (2.0 ± 0.5 m a^{-1}) than SIG (1.2 ± 0.5 m a^{-1}). Consequently, the more pronounced thinning at the tongue in comparison to SIG could be due to the quiescent phase after the surge.

Both parts of the ablation regions of SIG and NIG are covered by debris below ~ 3,500 m a.s.l. The surface of SIG showed considerable thinning rates but also great variability for both investigated time periods of ~1975 - 1999 and ~1975 - 2007. The surface lowering is higher at the frontal part of ~~the tongue despite thick~~SIG despite thick debris cover. This is in line with several other studies which found significant mass loss despite debris cover (Bolch et al., 2011; Kääb et al., 2012; Nuimura et al., 2012; Pieczonka et al., 2013). Field based measurements in 2005 of moraine thickness and ablation rates on the SIG revealed a dependency of ablation upon debris thickness with ablation rates from 2.8 to 6.7 cm/day with a mean of 4.4 cm/day (Hagg et al., 2008). The lower velocities and even immobility downstream of Lake Merzbacher indicate that there was little mass supplied from upstream. Therefore, the significant mass loss in debris-covered region can be explained by the influence of backwasting at ice cliffs and melting at supraglacial ponds (Fujita and Sakai, 2009; Han et al., 2010; Juen et al., 2014) but likely also to be a consequence of little mass gain from the accumulation region due to low flow velocities or even stagnancy~~reduced glacier flow from the accumulation region~~ (Benn et al., 2012, Bolch et al., 2012; Quincey et al., 2009; Schomacker, 2008).

Measurements at the Tian Shan Station (3,614 m a.s.l.) located 120 km west of SIG ~~suggested~~ revealed~~that both~~ increasing temperature and decreasing precipitation ~~were detected~~ during the ablation season (May-September) for the period 1970 - 1996; and a decreasing temperature and slightly decreasing precipitation was ~~also found~~ measured in the ablation season for the period of 1997-2009 (Krysanova et al., 2014; Osmonov et al., 2013; Reyers et al., 2013). ~~It~~ This is in disagreement with the observed climate change in the Tarim Basin where temperature increased after 1985 and annual precipitation increased after 1980 (Chen et al., 2009; Shi et al., 2006). Hence, the observed significant glacier mass loss between ~1975 and 1999 is most likely a consequence of the ablation season warming and precipitation decrease which led to an accelerated melting and less accumulation. Reduced mass loss of SIGor even the possible balanced condition between 1999 and 2007 can likely be explained by reduced ablation due to decreasing temperature decrease. However, increased mass loss of NIG between 1999 and 2007 can be explained by high mass loss at the tongue of NIG as -a result of strong advance in the mid 1990s.

56 Conclusion

We investigated glacier velocity, glacier area, surface elevation, and mass changes of Southern and Northern Inylchek glacier for the ~1975 - 2007 period based on multi-temporal space-borne datasets sources such as KH-9 Hexagon, Landsat, and SPOT-5 HRG data. Our results show that SIG has a velocity of about 100 m a^{-1} for large parts upstream of Lake Merzbacher with a main flow direction towards Lake Merzbacher and clearly lower velocities with likely stagnant parts downstream of the lake. Decreasing -velocities at the SIG tongue was found when comparing surface displacements in 2002/2003 to 2010/2011. In general, the area of the entire Inylchek Glacier system decreased in the ~1975 - 2007 period. However, NIG was surging later in 1996 which caused an overall area increase of 2.0 ± 0.1 km^2 (~1.3%) between ~1975 and 2007. The generated DEMs from ~1975 and 2007 were of good quality though partially missing information in the accumulation regions resulted in higher uncertainties. The results showed that the mass balance of both SIG and NIG was negative from ~1975 to 2007. despite the surge of NIG in the 1990s. A tributary surge was disclosed during 1999 and 2007 at SIG. However, the amplitude of both glaciers' mass loss is different. For SIG, decreased mass loss in the recent decade was observed with an overall mass balance for SIG wasof 0.42 ± 0.11 m w.e. a^{-1} between ~1975 and 2007. For NIG, on the other hand, increased mass loss between ~1975 and 2007 could be found since 1999; a mass balance of about -0.30 ± 0.11 m w.e. a^{-1} was measured for all the entire investigated time periods. Despite thick debris cover, surface lowering is highest at the distal part of the tongue of SIG where also low velocities are prevailing. The elevation thinning at the lake dam was shown to higher with a high flow velocity until the calving front, likely caused by calving into Lake Merzbacher. Thus, glacier thinning and glacier flow is significantly influenced by the lake.

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Figure and Table Captions

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Figure 2. Changes in glacier front position of SIG and NIG between ~1975 and 2007. The background Landsat TM image was acquired in 1990

Figure 3. Mean annual flow direction and velocity of SIG in the time intervals 2002 - 2003 (a) and 2010 - 2011 (b)

Figure 4. a: Elevation difference of SIG and NIG between KH-9 (~1975) and SRTM (1999); b: Elevation difference of SIG and NIG between SRTM (1999) and SPOT-5 (2007); c: Elevation difference of SIG and NIG between KH-9 (~1975) and SPOT (2007). The altitude of points a, b, c, d, e, f and g are ~3,080 m a.s.l., ~3,400 m a.s.l., ~3,860 m a.s.l., ~3,430 m a.s.l., ~3,685 m a.s.l., ~4,000 m a.s.l. and ~4,410 m a.s.l., derived from SRTM. Point a is on the edge of SPOT DEM and ALOS DEM. From the tongue of SIG to point a, the ice elevation differences are derived from KH-9 - ALOS in Figure 4b and SRTM - ALOS in Figure 4c. Point c and point e are on the boundary of KH-9 in 1974 and KH-9 in 1976; Region 2 is in accumulation of SIG in Figure 4b.

Figure 5. Longitudinal profiles of SIG and NIG for the period ~1975 - 1999 (KH-9 - SRTM), 1999 - 2007 (SRTM - SPOT). The section of ALOS PRISM between the tongue of SIG and point a was derived from SRTM - ALOS in black line.

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Table 1. List of utilized satellite images and data sources

Satellite	Time	Pixel size (nadir, m)	Swatch(Km)	B/H	DEM pixel size (m)	Velocity image
ALOS Nadir(N) Backward(B)	Oct., 08, 2006	2.5	35	0.5	10	-
SPOT-5 HRG	Feb., 05, 2008	2.5	60	0.63	10	-
SRTM3 Unfilled Finished version	Feb., 2000		1°*1°（tile size）	-	90	-
SRTM3 filled version	Feb., 2000		1°*1°（tile size）	-	90	
Landsat ETM+	Oct., 13, 1999	15	185	-	-	-
Landsat TM	Sept., 10, 1990	30	185	-	-	-
KH-9 Hexagon	Nov., 16, 1974	6-9	240*120		25	-
KH-9 Hexagon	Jan. 16,1976	6-9	240*120		25	-
Terra ASTER	Aug. 25, 2002	15	60			Yes
Terra ASTER	Aug. 28, 2003	15	60			Yes
Landsat TM	Aug. 16, 2010	30	185			Yes
Landsat TM	Aug. 3, 2011	30	185			Yes

Table 2. Uncertainty of glacier delineation (%)

	SIG				NIG			
	Landsat TM	KH-9	Landsat ETM+	SPOT-5	Landsat TM	KH-9	Landsat ETM+	SPOT-5
Landsat TM	2.2	2.7	2.4		3.1	3.7	3.4	
KH-9		1.5	-	1.6		2.1	-	2.1
Landsat ETM+		-	1.0	1.0		-	1.5	1.6
SPOT-5	-		-	0.3	-		-	0.6

Table 3. The SIG and NIG area change between ~1975 and 2007

Year/period	Area/Area change	SIG	NIG
~1975	Area (km^2)	508.4 ± 7.6	156.6 ± 3.3
~1975 - 1990	Area change (km^2)	-0.1 ± 0.1	-1.2 ± 0.1
	Area change (%)	-	-0.8
	Annal area change (km^2 a^{-1})	-0.007 ± 0.007	-0.08 ± 0.007
1990 - 1999	Area change (km^2)	-0.5 ± 0.1	3.7 ± 0.1
	Area change (%)	-0.1	2.4
	Annal area change (km^2 a^{-1})	-0.056 ± 0.011	0.411 ± 0.011
1999 - 2007	Area change (km^2)	-0.2 ± 0.1	-0.4 ± 0.1
	Area change (%)	-	-0.3
	Annal area change (km^2 a^{-1})	-0.025 ± 0.013	-0.050 ± 0.013
~1975 - 2007	Area change (km^2)	-0.8 ± 0.1	2.0 ± 0.1
	Area change (%)	-0.2	1.3
	Annal area change (km^2 a^{-1})	-0.025 ± 0.003	0.063 ± 0.003

Table 4. Glacier mass changes based on Area-averaged dh/dt for period ~1975 - 2007

			Altitude zone(m a.s.l.)	Area covered by DEM (km^2)	Percentage of total area (%)	Glacier mass changes (m w.e.a^{-1})
SIG	SRTM-KH9	~1975-1999	2,900-6,600	374.5	73.9	-0.43 ± 0.10
	SPOT-SRTM	1999-2007	3,000-6,600	241.7	47.6	-0.28 ± 0.46
	SPOT-KH9	~1975-2007	2,800-6,600	388.6	76.43	-0.42 ± 0.11
NIG	SRTM-KH9	~1975-1999	3,300-6,300	107.5	67.6	-0.25 ± 0.10
	SPOT-SRTM	1999-2007	3,300-6,400	62.7	39.2	-0.57 ± 0.46
	SPOT-KH9	~1975-2007	3,400-6,600	109.9	69.1	-0.30 ± 0.11

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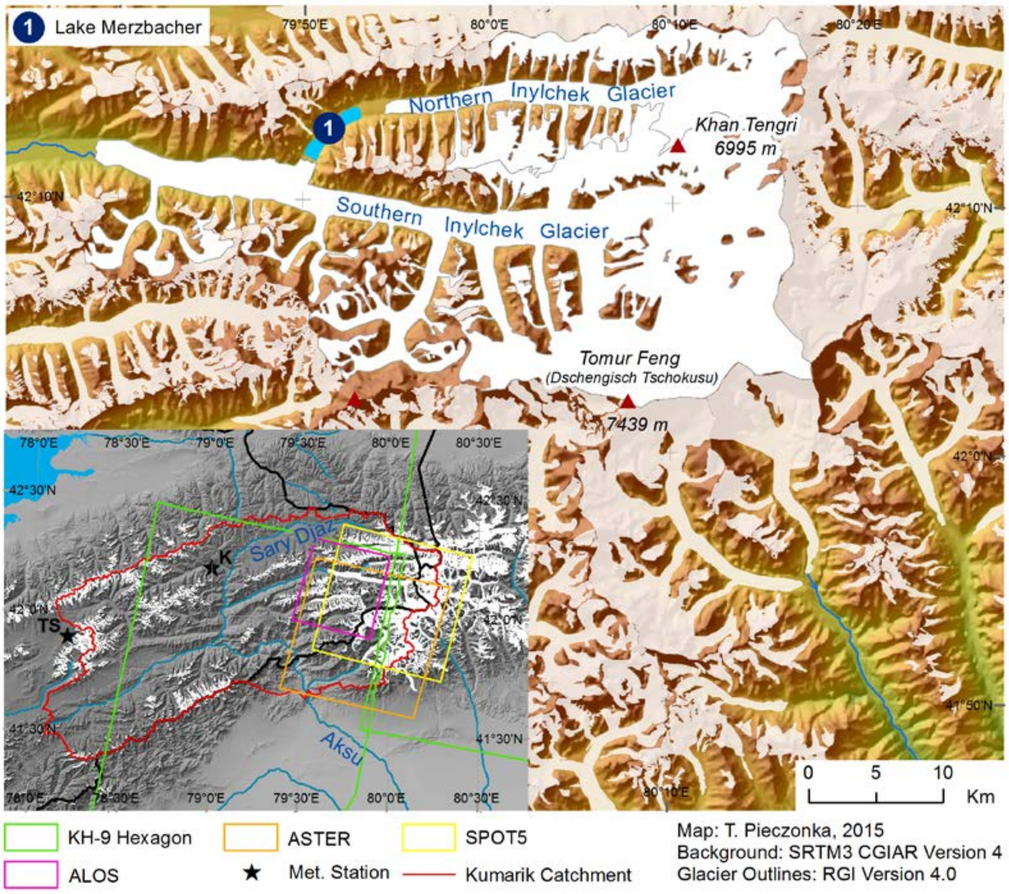

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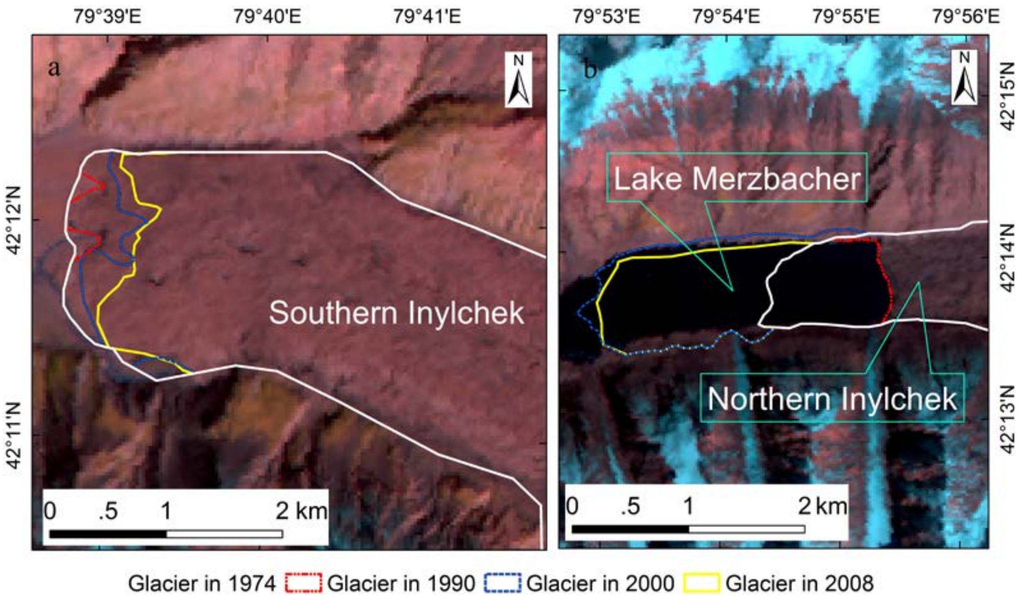

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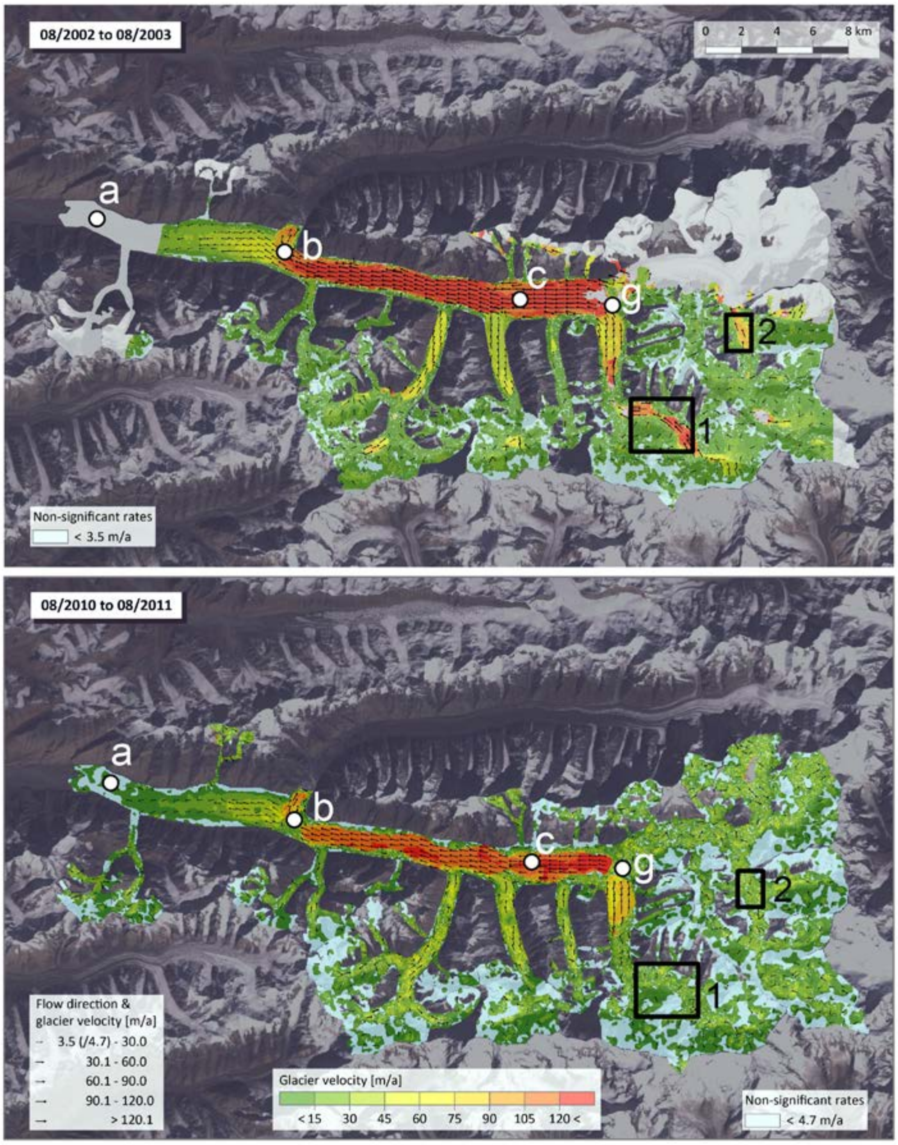

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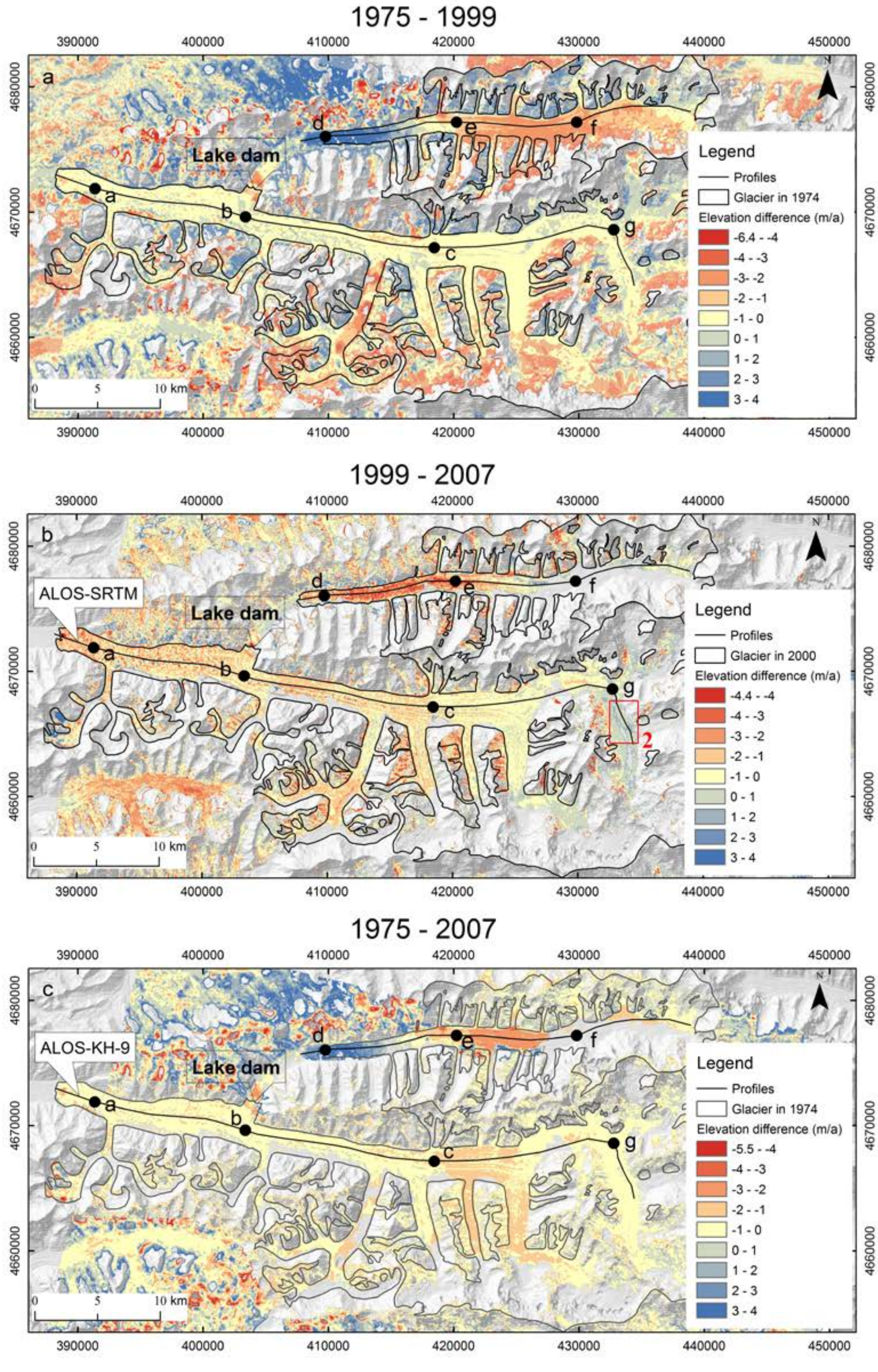
1975 - 1999
a
Lake dam
a
b
c
d
e
f
g
Legend
Profiles
Glacier in 1974
Elevation difference (m/a)
-6.4 - -4
-4 - -3
-3- -2
-2 - -1
-1 - 0
0 - 1
1 - 2
2 - 3
3 - 4
0 5 10 km
1999 - 2007
b
ALOS-SRTM
Lake dam
2
Legend
Profiles
Glacier in 2000
Elevation difference (m/a)
-4.4 - -4
-4 - -3
-3 - -2
-2 - -1
-1 - 0
0 - 1
1 - 2
2 - 3
3 - 4
0 5 10 km
1975 - 2007
c
ALOS-KH-9
Lake dam
Legend
Profiles
Glacier in 1974
Elevation difference (m/a)
-5.5 - -4
-4 - -3
-3 - -2
-2 - -1
-1 - 0
0 - 1
1 - 2
2 - 3
3 - 4
0 5 10 km
390000
400000
410000
420000
430000
440000
450000
4660000
4670000
4680000

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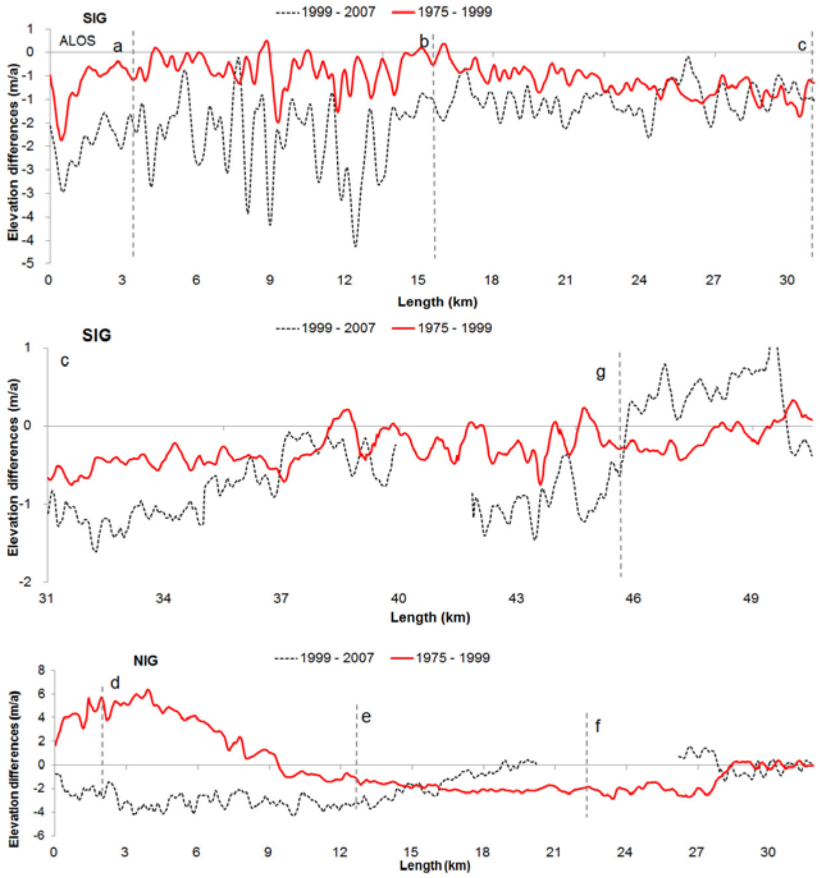

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