Coverletter

Multi-decadal mass balance series of three Kyrgyz glaciers inferred from modelling constrained with repeated snowline observations.

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Dear Editor,

The two constructive reviews were very helpful to finalize the paper. In particular, we have
- adjusted the title and reworked the terminology,
- justified the independence of mass balances determined with in-situ point measurements with additional model experiments,
- completed and improved the description and calculation of geodetic mass change and
- added statements concerning a broader applicability of the snowline approach

Below, we respond to all comments, and state how we account for them in the revised version of the paper. The responses (normal font style) to the reviewers' comments are written directly into the reviews (displayed in italic font style). The corresponding revised sentences in the manuscript are given in quotation marks, including page and line numbers in the revised manuscript.

Comments of Reviewer #1 (Anonymous)

(1) Title of the paper The title of the paper is misleading and needs to be changed. Indeed, in your approach the surface mass balance is modelled with meteorological data and this modelling is constrained by snowline observations during the ablation season. Thus, the title has to mention that the surface mass balance time series are quantified with a model. As it stands, one can have the impression that the surface mass balance is only inferred from snowline observations. I suggest: "Glacier surface mass balance modelling constrained by remote sensing derived snowlines. Application on three kyrgyz glaciers to quantify multi-decadal series". Or "The use of remote sensing derived snowlines to constrain glacier surface mass balance modeling. Application on ..."

We agree that the title did not make reference to the modelling behind the approach, and adjusted it as suggested by the reviewer to "Multi-decadal mass balance series of three Kyrgyz glacier inferred from modelling constrained with repeated snowline observations."

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(2) Name of the proposed approach. In the same way, the name you give to the proposed approach (snowline-derived mass balance) is not adequate, and so is the abbreviate in the tables and figures (Msnl). For the name of the approach, I propose: Modeled SMB constrained by snowline. And

for the abbreviate: Mmod-tsl. TSL stands for Transient Snow Line and must be preferred to SNL.

The name of the method was adjusted to "modelled SMB constrained by snowline observations"and we changed SNL to TSL throughout the entire manuscript. We also use "snowline approach"to refer to the method using a mass balance model constrained by snowline observations.

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(3) Terminology. "Mass balance", "glacier balance", etc: Be careful with the terminology and follow Cogley and others Glossary of mass balance terminology. For example, use "surface mass balance"instead of "mass balance"or "glacier balance", except when you refer to the geodetic mass balance.

The terminology has been adjusted in the new version of the manuscript and we use surface mass balance wherever it is referred to. However, please note that when the modelled mass balance constrained by snowline observations is compared to geodetic mass balances, we do not refer to the surface mass balance but to a total mass change that includes an estimate of internal / basal mass balance.

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(4) Glaciological surface mass balance. The used method is not the classical glaciological one. Indeed, a model-based extrapolation is used and optimized to best fit the point measurements. What about the input data for accumulation and ablation (e.g. precipitation and temperature data)? Where do they come from? Are they the same as used in the model constrained by the snowline? If the data are the same, are the methods "constrained by the snowline observations" and "constrained by the point measurements"strictly independent as they rely on the same meteorological data?

This is an interesting and thoughtful question. Indeed, the same meteorological input is used for both approaches. However, we are convinced that both approaches can be considered as independent out of the following reasons:

The mass balance model used to derive the glaciological series is not regarded as a physical model, but as a statistical tool for obtaining glacier-wide surface mass balances based on field data and is closely tied to the field surveys. It is thus just a way to compute glacier-wide mass balance from stake measurements (such as the profile or the contour method). No model-based temporal extrapolation, e.g. to the hydrological year is involved. Consequentially, the climate data used in the model-based extrapolation of point mass balances permits spatial extrapolation to the entire glacier using physically-based equations and does not affect year-to-year variability which is given by the in-situ measurements. Here, we avoid the use of daily mass balance variability, and refer strictly to the surface mass balance obtained for the measurement dates.

In response to the reviewers comment we performed a sensitivity test to prove the limited impact of the used meteorological time series on the glacier-wide mass balance computed from in-situ point measurements. We use artificially perturbed air temperature ($\pm 1°$C) and precipitation ($\pm 25\%$) series. The standard deviation in the inferred glacier-wide surface mass balances is less than 0.01 mm w.e. yr^{-1} for all three glaciers and all years. This indicates that the method used to compute glaciological mass balance from in-situ field data exhibits a very small sensitivity on the actual meteorological data used for driving the mass balance model. The calculated annual glaciological SMB depends thus strongly on the in situ ablation and accumulation measurements and is considered as independent from the snowline approach. We tried to clarify the role of the meteorological data for the glaciological method used here, and added the results of the sensitivity test.

Page 9, Lines 10-15

"A model-based spatial extrapolation of point measurements to the entire glacier surface after Huss et al. (2009) was used to retrieve glacier-wide SMB for all years with direct measurements. The model is a combined distributed accumulation (Huss et al., 2008) and temperature-index melt model with daily resolution (Hock, 1999) which was automatically optimized to best represent all collected point data from each seasonal/annual survey. The model is considered as a suitable tool to extrapolate the glaciological point measurements to the glacier surface for the measurement periods."

Page 14, Lines 6-9

"For a sensitivity experiment we artificially shifted temperature and precipitation series used for the model-based extrapolation by $\pm 1^{\circ}$C and $\pm 25\%$, respectively. The resulting glacier-wide SMB indicate a very small sensitivity to the meteorological input data with a Standard Deviation (STD) of $<0.01\,\mathrm{mm\,w.e.\,yr^{-1}}$. We strictly refer to the annual SMB obtained for the measurement dates that are listed in table 2."

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(5) High resolution images recorded in November - impact of the snow cover on the derived DEM. Two of the stereo-pairs used to make DEMs and quantify the geodetic mass balance were recorded in November for Abramov and Golubin glaciers, respectively. I had a look at the SPOT catalogue and for Golubin I could find the SPOT7 images from 01/11/2014. Regarding Abramov, the images are not in the catalogue but I assume it is because these have been acquired within the SPIRIT acquisition campaign. Anyway, at least for 2014 and I assume it is the same for 2011, all the more because the SPOT5 images date from late November, the glaciers and surrounding terrains are completely snow covered. This implies several challenges for DEM generation:

- low contrast because of snow brightness

- unknown snow thickness

- impossibility to delineate the glacier outline.

How these issues have been tackled and what is their impact on the uncertainties? In addition, Table 7 shows that the geodetic mass balances for Abramov (2011-2015) and for Golubin (2006-2014) are less negative that the average annual surface mass balances quantified by your model constrained by the snowline. Can the snow-cover on the images implying a higher surface elevation (of an unknown value!) be a cause of this difference (or at least part of it)?

This is an absolutely justified comment and we are aware that the quality of the two November scenes is not ideal. However, we are convinced to have extracted valuable information from the two images. Low contrast in the upper accumulation area due to fresh snow-cover and shading from steep mountain walls led to data gaps indicated as unmeasured areas on the glacier surface (26% for Abramov and 30% for Golubin, see also Figure 7 for Golubin). We accounted for the unmeasured areas on the glacier surface with a five-fold increase in uncertainty (see Section "Uncertainties and Sensitivity"). The retrieved information for the remaining glacier area appeared nevertheless reliable. Also, the problems with low visual contrast are much reduced for modern sensors (here: 12 bit) and careful gain management, compared to older 8 bit sensors that often showed saturation over snow. In essence, in our cases there was over large areas sufficient contrast for parallax matching even over snow.

We agree with the reviewer regarding the issue of the unknown snow thickness. In principle, snow cover introduces a systematic bias into the calculation of geodetic volume change that needs to be accounted for. As it is unknown how deep the snow was on the glacier during the acquisition of the imagery we take a simple but efficient approach and account for the snow coverage by co-registering the digital elevation models using snow-covered stable ground sections. In this way, we approximately correct for the fresh snow on one of the scenes. This has been done for Abramov already in the first version of the submitted manuscript. However, for Golubin the vertical offset correction has now been adapted to systematically include snow-covered stable terrain sections. In addition, we compared the offset inferred using this approach to snow depth measurements at the Automatic Weather Station installed at 3300 m a.s.l. on the 1 of November 2014 and found good agreement. The geodetic mass balance was corrected from -0.22 to $-0.30\,\mathrm{m\,w.e.\,yr^{-1}}$. which indeed shows a better agreement between the snowline-constrained model results and the geodetic mass balance for Golubin Glacier.

The outlines have been drawn on snow-free satellite images of other sensors as stated in Section "Glacier outlines". We did not include an error related to the delineation of the outlines in our error estimate.

In addition to the above correction, we have added some sentences about snow-cover conditions in the Study Site and Data section of the revised paper and have better described the approach to account for snow cover using the offset correction. Please note that especially for the geodetic mass balance of Golubin Glacier, it was difficult to find appropriate high-resolution images. The estimated uncertainties are considerably higher when snow-covered images were used than for the other geodetic estimates.

Page 5, Lines 27-29

"Important snow coverage was present on the SPOT5 image from 2011 for Abramov and on the SPOT7 image from 2014 for Golubin. A fine layer of fresh snow covered parts of the SPOT6 image from 2015 for Glacier No. 354."

Page 10, Lines 4-6

"For this vertical co-registration, only terrain sections with a slope smaller than 30 ° were selected and areas with parallax-matching problems were avoided. Snow-covered areas were included in the offset correction, in order to correct for fresh snow on the image, assuming similar snow thicknesses on- and off-glacier."

Page 19, Lines 17-19

"The geodetic method reveals a total mass balance of $-0.30 \pm 0.37\,\mathrm{m\,w.e.\,yr^{-1}}$ for Golubin Glacier from 8 September 2006 to 1 November 2014 (Fig. 10). The corresponding total modelled mass balance constrained by snowline observations was slightly more negative with $-0.38 \pm 0.35\,\mathrm{m\,w.e.\,yr^{-1}}$ for the same period (Table 8 and Fig. 11)."

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(6) Surface mass balance interannual variability. It is pity that your discussion about the interannual variability of the SMB is short and only dedicated on the annual values. You should

have a look on the two terms of the annual surface mass balance, and discuss about their interannual variability. You could see if the interannual variabilities of accumulation and ablation are homogeneous, comparable between the three sites and if the difference you mention regarding the interannual variability of Glacier No. 354 annual SMB is more likely related to a different ablation or accumulation interannual variability.

We agree with the reviewer in general. An analysis of the interannual variability would be very interesting and insightful. However, the data sets available in this study (annual in-situ point mass balance, decadal geodetic mass balance, repeated snowline observations) only allow us to directly constrain annual mass balances. Seasonal and daily mass balances, calculated by the snowline-constrained model are not tied directly to any observations and day-to-day variability depends on partly uncertain meteorological information. Therefore they are subject to larger unknown uncertainties. Furthermore, the calibration of the two parameters DDF_{snow} and C_{prec} are not strictly independent and thus could lead to important under- or overestimations of the two seasonal components of the modelled surface mass balances. This shortcoming of the method is described in Section "Discussion" and shown in Figure 13b. Unfortunately, at the current stage, we only have a few seasonal in situ measurements for the studied glaciers. A reliable verification of the performance of the snowline approach in terms of the winter and summer surface mass balance is thus not possible. For the above-mentioned reasons we avoid an interpretation of the interannual variability here.

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(7) Application of the proposed approach. You mention that the approach you propose can be useful to quantify surface mass balance time series for a number of remote glaciers. Although I mostly agree with this statement, I wonder if the approach can indeed be applicable for summer accumulation glaciers (like in the tropics, or in monsoon regime regions) or for high latitudes glaciers where superimposed ice can be more important than in Kyrgyzstan. You can probably add some sentences on this point in the conclusion.

We added some sentences on the potential wider applicability of the proposed approach in the Discussion section of our manuscript. However, we are unable to perform a complete assessment of the transferability of our approach to other climate zones in the scope of the present study.

Page 24, Lines 17-24

"SMBs inferred from the snowline approach are closely tied to the representativeness of snowline observations. The method might be able to yield reliable SMB estimates for many glaciers in different climatic regimes, for which the transient snowline is an indicator of the surface mass balance. The relationship between the snowline and the SMB can however be importantly challenged when the position of the transient snowline is blurred by fresh snow or superimposed ice. The applicability of the snowline approach presented here can thus be critical when the transient snowline on remote sensing data cannot unambiguously be identified. This is mainly a problem for glaciers with a summer accumulation regime due to frequent fresh snow falls, and glaciers with a high relevance of superimposed ice."

Specific comments:

Abstract

P1, L5-6: the sentence "A combination of 3 independent [] Golubin and No. 354"needs to be reformulated. Indeed, the methods are not combined to reconstruct the surface mass balance. The methods are compared/cross-validated but not combined. For me, you would have a combination if, for example, your modeled surface mass balance time series had been adjusted with the geodetic method.

Reformulated.

Page 1, Lines 5-7

"By cross-validating the results of three independent methods, we reconstructed the mass balance of the three benchmark glaciers, Abramov, Golubin and No. 354 for the past two decades."

P1, L8-9: "satellite optical imagery"instead of "satellite imagery".

Done.

P1, L12, 13 and in the entire paper: should write "yr-1", instead of "a-1". "yr-1"is most common except for IGS journals.

Done.

P1, L15: prefer "unmonitored"to "inaccessible". I do not know about an inaccessible glacier on Earth."

Done.

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1. Introduction

P2, L2: should the IPCC reference be quoted Stocker et al. (2013)

Referencing has been changed.

P2, L18: remove a comma after "e.g.,"

Done.

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2. Study site and data

P4, L12-13: this statement is useless if you do not give any quantification.

Quantification has been added.

Page 4, Lines 11-13
"For Golubin, the geodetic mass loss reported by Bolch (2015) was -0.28 ± 0.96 m w.e. yr^{-1} from 2000 to 2012, whereas Brun et al. (2017) found a geodetic mass balance of -0.04 ± 0.19 m w.e. yr^{-1} for the period 2002 to 2013."

P5, L11-12: idem, give a value.

Quantification has been added.

Page 5, Lines 11-13
"Mass loss since the mid-1970s was reported by different studies ranging from about -0.8 to -0.5 m w.e. yr^{-1} (Brun et al., 2017; Kronenberg et al., 2016; Pieczonka and Bolch, 2015) ."

P5, L6 and 15: should mention the elevation of the AWS

Done.

Figure 3: for Glacier No. 354, the Quickbird and Pliades images recorded in 2003 and 2015 respectively have not been used for snowline mapping? If yes, these images should appear in the Figure. If not, why?

The QuickBird image has not been used for snowline mapping because it dates from summer 2003, and the first year to compute was the year 2004. We clarified in the caption and manuscript text.

Page 7, Figure 3
"Image availability and distribution for snowline mapping. Numbers indicate the total available scenes per year and glacier. Prior to 1998, image coverage is sparse for all three glaciers. For Golubin and for Glacier No. 354, the first summer season for which enough snowline observations could be collected was 2000 and 2004, respectively. Snow-covered high-resolution images have not been used to delineate the snowline and are not shown here."

Table 1: should write "snowline"instead of SNL. You should also indicate the sensor in brackets for the high resolution images. If I am correct these are SPOT5 and Pliades for Abramov, ALOS

and SPOT7 for Golubin and Quickbird, GeoEye and Pliades for No. 354.

Done.

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3. Methods

See my main comment related to this section (no4), and the one regarding the terminology for the title of this sub-section.

Please refer to the answer given for the main comment No. 4.

P10, L23: the paper by Huintjes and others has not been finally published. I wonder if papers that stayed in discussion and/or were rejected can be quoted. You can probably remove this reference from the text and the ref list, all the more that it is quoted within a list of 5 references starting by e.g.

The reference has been removed.

In Table 2 and in the text (e.g. P11, L7): I recommend using Z instead of H for the elevation criteria. H usually stands for thickness.

Done.

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4. Uncertainties and model sensitivity

P15, L3-8: you should provide an illustration for the test that uses average daily temperature and precipitation series. In addition, you have to explain the low sensitivity of your model to the input meteorological data. I assume this is because the parameters are adjusted for each year and for each glacier.

An illustration has been added and we have extended our explanation on the low sensitivity of the model to the meteorological input data (see Fig. 6)

Page 15, Lines 27-30
"These results demonstrate a relatively low sensitivity of our model approach to daily meteorological input data. With the chosen calibration procedure the model parameters DDFsnow and C_{prec} are adjusted to best represent the TSL observations for each year and glacier individually. The modelled SMB are thus closely tied to the snowline observations and exhibit a reduced dependence from meteorological input data."

Figure 5b: change JAJ by JJA

Done.

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5. Results

P16, L3-6: you should provide an illustration for the comparison between SCAFs given by the model and the images for all the used images, glacier by glacier.

We added an illustration comparing the observed and modelled SCAF for each glacier (see Fig. 7).

P16, L7-8: the period 1998 to 2016 stands for Abramov Glacier only. You have to mention the specific periods for each glacier. Golubin starts in 2000 and No. 354 in 2004. In addition "over the two last decades"can be removed from the sentence because the time periods for each glacier will be mentioned.

Done.

Page 18, Lines 3-5
"Annual glacier-wide modelled surface mass balances constrained by snowline observations, calculated for Abramov (1998-2016), for Golubin (2000-2016), and for Glacier No. 354 (2004-2016), located in the Pamir-Alay and the Tien Shan, are predominantly negative (Fig. 8 and Tabel 6)".

P16, L8: you refer to Figure 8, but because figures 6 and 7 have not been quoted yet, this figure should be Figure 6. Anyway, because I suggest adding two more figures, it will probably remain Figure 8, but must appear before the current figures 6 and 7.

Numbering has been corrected.

Table 5: you must indicate in the table itself (not only the caption) on which period the STD is quantified

We removed the STD from the table but included a statement directly into the text.

Page 18, Lines 12-14
"A lower standard deviation of annual mass balances from 2004 to 2016 is found for Glacier No 354 (0.19 m w.e. yr^{-1}) than for Golubin (0.4 m w.e. yr^{-1}) and Abramov (0.29 m w.e. yr^{-1}), which indicated higher interannual variability for the latter two."

P17, L1: should the first close-to-zero SMB period be extended to 2005?

We agree and extended the period to 2005.

P17, L1: "Glacier No. 354, situated in a more continental climate regime, []". I am a bit skeptical with this statement! All three glaciers are in a continental regime. This glacier being located in the inner range, it might receive less precipitation than the two others. Is it what you mean? See also my main comment related to interannual variability of the SMB (no6).

Indeed, we refer to a strong precipitation gradient from West to East for both the Pamir/Pamir-Alay and the Tien Shan and also a different precipitation distribution. Glaciers in the western part of the Tien Shan receive more winter accumulation whereas glaciers located more in the east are subject to considerable summer accumulation. This corresponds to the general synoptic large-scale meteorological conditions over Central Asia, influenced by the main direction of the zonal flow of the air masses from west to east. According to Balashova et al. (1960) and Schiemann et al. (2008) also meridional air mass flow can occur. This occurs either in situations when tropical air masses enter from South and south-west or when north-westerly, northerly and sometimes even north-easterly, cold air masses intrude into Central Asia. We specified the statement but do not want go into more detail in the manuscript.

Page 18, Lines 14-15

"Glacier No. 354, receiving lower amounts of total annual precipitation, showed a smaller mass turnover and had a positive balance only in 2009 (Table 6)."

P17, L4-5: this sentence refers to the years 2006 and 2008 mentioned in the previous sentence? If yes, the two sentences might be separated by a semi-colon not a dot.

Done.

P17, L8-9: same thing here, the two sentences could be separated by a semi-colon not a dot.

Done.

Table 6: you should mention in the caption that the values differ from Table 5 because the glacier-wide annual surface mass balances are not computed over the same number of days. However, the difference is really high for some years, for example 2014 for Golubin Glacier (more than 0.8 m w.e. different!). You could indicate the number of days differing from the quantification given in Table 5.

Instead of indicating the number of differing days, we added a table with the exact survey dates, and changed the statement in the caption to underline the difference to Table 5.

Page 20, Table 7

"Annual SMB $B_{\mathrm{sfc(meas)}}$ for the measurement periods (i.e., exact dates of the surveys Table 2) based on direct glaciological measurements and on the snowline-constrained model for the three glaciers in m w.e yr^{-1}."

Table 7. A dot is missing after e in "m w.e a-1"In addition, regarding Abramov Glacier, why the first period is 2003-2015 and not 2003-2011?

Due to the limited image quality of the SPOT image from November 2011, we considered the mass balance from 2003 to 2015 to be more robust, and decided to show the result for this period instead.

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6. Discussion

P20, L3: replace "integrating"by "using"

Done.

P21, L6: discuss why the difference is opposite for Glacier No. 354

We discovered an error in the model settings of Glacier No. 354 of the unconstrained model leading to the too positive balance for Glacier No. 354. The error is corrected and we would like to apologize for this mistake. The calculations and figures are now updated (see Fig. 12). Not surprisingly, the mass balance is much more negative for the unconstrained run.

P22, L27: replace "too positive"by "not negative enough"

Done.

P22, L33: change "shows"by "showed"

Done.

P23, L18-20: you indicate that the average glacier-wide annual surface mass balance quantified by Brun et al. (2017) shows a stronger mass loss than your study. This is not really exact. The difference is important with your modeling approach, but the estimate by Brun and others and your geodetic estimate are really close.

We clarified our statement.

Page 26-27, Lines 30-2

"The average mass balance for Abramov of -0.38 ± 0.10 m w.e. yr^{-1} (2002-2014) derived by Brun et al. (2017)

using multi-temporal ASTER DEMs indicates a stronger mass loss than the results obtained with the snowline approach. We note, however, that the start and end dates of their geodetic mass balance assessment represent a mean over a mosaic of different dates, thus hampering direct comparison. In addition, the differences are still within their error bounds. The results by Brun et al. (2017) are, in line with the geodetic mass balance calculated in the present study for the period 2003 to 2015 based on high-resolution satellite images."

Comments of Reviewer #2 (Prof. Dr. M. Pelto)

2-8: signification to significance

Done.

2-15. Be consistent on spelling of Urumchi

This has been corrected through the entire manuscript. We use Urumqi.

3-3: Change Pelto (2011) toPelto et al. (2013)

Done.

Figure 3: Conveys important information, this could just as easily be conveyed in a table if there are production advantages to that

We prefer to illustrate the image availability in a figure rather than in a table. The individual image dates are not very important in this context. However, we would like to sketch the increased image availability with time which, in our opinion, becomes more evident with a figure.

5-14: Is the superimposed ice evidence indicative of persistent or transient existence?

The superimposed ice zone is rather persistent. We clarified this in the manuscript.

Page 5, Lines 14-15
"Evidence of persistent superimposed ice is found and Kronenberg et al. (2016) estimated internal accumulation to be $+0.04\,\mathrm{m\,w.e.\,yr^{-1}}$."

7-7: Later in the paper it is worth simply mentioning the overall retreat observed on the three glaciers and how that fits into the negative balance regime.

We added some statements on the retreat pattern of the glaciers and brought it into context with the negative balance regime in the Discussion section.

Page 18, Lines 6-12
"For Golubin and Glacier No. 354 a slightly more negative annual average balance of $-0.41 \pm 0.33\,\mathrm{m\,w.e.\,yr^{-1}}$ and $-0.36 \pm 0.32\,\mathrm{m\,w.e.\,yr^{-1}}$, respectively, was calculated for the same time period (Table 6). Length change

measurements underline the observed negative balance regime of all three glaciers (Hoelzle et al., 2017). A significant glacier retreat was observed for the last century. A first speed-up of frontal retreat occurred in the 1980s and acceleration was observed in the last decade. However, no clear acceleration of mass loss for the three glaciers was identified over the investigated periods. Two phases of close-to-zero SMB could be recognized (2002-2005 and 2009-2011) for all glaciers."

8-18: Given that a couple of the references are related to the study I would add Mernild et al. (2013) Pelto et al. (2013) where this is also discussed and are already references used elsewhere in paper.

Done.

8-25: Is the contrast with snow to firn weak for the terrestrial camera or just satellite images?

Clarified.

Page 8, Lines 29-31

"Contrast becomes rather weak, especially when the snowline rises above the firn line (Rabatel et al., 2013; Wang et al., 2014) for both satellite and terrestrial camera images."

9-4: The initial position being the GPS location at the time of emplacement?

The GPS measurements of the glacier front position were repeated every year.

Page 8, Lines 1-2

"Annually repeated measurements of the glacier front position using a handheld GPS for all three glaciers were combined with the satellite observations for mapping from 2011 onward."

9-9: The extrapolation indicated is spatial. Given the field seasons occur before the end of the ablation season, is this also a temporal extrapolation model or is this different. Just clarify temporal from spatial extrapolations.

Clarified in the manuscript. The extrapolation is only spatial. We did not adjust the glaciological mass balance for the start and end date of the hydrological year, but calculated the mass balance derived with the snowline approach to match the dates of the direct measurements for comparison.

Page 9, Lines 10-15

"A model-based spatial extrapolation of point measurements to the entire glacier surface after Huss et al. (2009) was used to retrieve glacier-wide SMB for all years with direct measurements. The model is a combined distributed accumulation (Huss et al., 2008) and temperature-index melt model with daily resolution (Hock, 1999) which was automatically optimized to best represent all collected point data from each seasonal/annual survey. The model is considered as a suitable tool to extrapolate the glaciological point measurements to the glacier surface for the measurement periods."

9-30: Given the issues described what is the vertical accuracy generally achieved? This is I think discussed at 13.24, but is appropriate here too.

We added the vertical accuracy.

Page 10, Lines 6-8

"The vertical accuracy was thus improved, and the mean absolut difference off-glacier was limited to 1.0 m (2003-2015) and 0.6 m (2011-2015) for Abramov, 0.7 m for Glacier No. 354 and 1.6 m for Golubin (see also Section 4)."

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*10-8: Is the approach what Pelto (2010) and Mernild et al. (2013) utilized which is TSL migration rate * balance gradient? This yields a directly observed ablation rate.*

No, we did not use the same approach as presented in Pelto (2010) and Mernild et al. (2013). These approaches integrate direct field measurements to calculate snow ablation rates which are not consistently available for our study region. Here, we use an iterative modelling approach to calculate snow accumulation and use only TSL as input. Please refer to Section 4.3 that gives details on the model constrained by snowline observations.

11-1: Why is the DDFs for Golubin very close to the maximum?

Thanks for spotting this. It was an error in the submitted manuscript. The mean DDF is $5.09\,\mathrm{mm\,day^{-1}\,{}^{\circ}C^{-1}}$ and not $5.49\,\mathrm{mm\,day^{-1}\,{}^{\circ}C^{-1}}$. We apologize for this mistake.

13-6: Geodetic mass balance calculations do not account for internal accumulation either, unless it is incorporated in the density calculations, which typically does not occur.

This is a very interesting comment on the problem of geodetic mass balance computations. We are however unable to fully resolve this issue in the present paper. We completely agree with the reviewer that the density assumption to calculate the geodetic mass balance is critical and so far not well understood. In principle, the geodetic mass balance, however, includes all mass changes within a glacier, and not only surface processes. The problem goes back to the density assumptions of converting volume to mass changes.

We are sure that a correction is needed for unifying surface mass balances with geodetic surveys that monitor all mass change components. However, as stated by the reviewer, to correctly account for internal accumulation within the geodetic mass balance, a correct density assumption is required. Yet, this is not straight-forward, and we believe that improving the confidence in volume-to-mass change density assumptions is not possible within the scope of this study and more process-related studies on this subject are required. We are aware that chosen density assumption is a strong simplification but at the current stage, we are simply not able to reasonably correct the calculated geodetic mass balance for the component of internal accumulation. This is why we have chosen an error ranges for the volume-to-mass conversion which are expected to cover the respective uncertainties.

13-29: Why this choice of 120 kgm-3, and what are implications vs a less conservative choice?

As mentioned above, the density assumption is very critical to convert volume to mass change. Currently, we have unfortunately not enough knowledge to make more adequate assumptions. Nevertheless, we decided to use a more conservative volume-to-mass conversion and simply doubled the uncertainty range of the density for periods shorter than 3 years.

15-7: "These results demonstrate a relatively low sensitivity of the presented model to daily meteorological input data compared to mean seasonal data...".

The sentence has been changed according to the comments of reviewer 1.

Page 15, Lines 27-30

"These results demonstrate a relatively low sensitivity of our model approach to daily meteorological input data. With the chosen calibration procedure the model parameters DDF_{snow} and C_{prec} are adjusted to best represent the TSL observations for each year and glacier individually. The modelled SMB are thus closely tied to the snowline observations and exhibit a reduced dependence from meteorological input data."

16-10: Section 4 was an excellent detailed summary of the approach to determining errors and sensitivity. How did that lead to the error numbers here which are somewhat higher than I expected after seeing the details in Section 4.

We combined the different error sources for each year by the Root Sum of Squares, assuming independence between the different error components and averaged the annual errors for the considered periods. We clarified this in the manuscript.

Page 17, Lines 1-3

"Components 1 to 5 are assumed to be independent of each other and are combined as RSS to represent the total error of the annual SMB σ_{tsl} obtained from the snowline approach. We then averaged the annual error over the different periods to compute overall uncertainty."

18-9: The more negative balance years on Golubin and Abramov is where the TSL method generates more negative results. Could this be a reflection of melt low on glacier outside of ablation season that TSL does a better job of capturing? If this cannot be addressed to advantage than *do not.*

As the daily mass balance evolution is a pure product of our modelling approach and per se not actually constrained by the available observations (in contrast to the annual mass balance), we prefer to leave aside interpretations on the seasonal components of the surface mass balance (see also comment to reviewer 1 above).

21-1: Could utilize Shea et al. (2015) as well for support they found almost the same value for the Mount Everest region, different climate setting but still a high altitude monsoon influenced area. Wu et al. (2011) also determine DDFs for Urumqi Glacier that could be referenced

We integrated the suggested references to underline the choice of our parameters.

Page 22-23, Lines 6-3

"We chose C_{prec} to account for a 20%-measurement error of observed precipitation (Sevruk, 1981), and a combination for DDF_{ice} (7.0 mm day^{-1} °C^{-1}) and DDF_{snow} (5.5 mm day^{-1} °C^{-1}) as recommended by Hock (2003) for the former Soviet territory, for all three glaciers. Similar values were used to model glaciers in the Tien Shan and Himalayas (e.g. Shea et al., 2015; Wu et al., 2011; Zhang et al., 2006)."

21-6: Why the large divergence for Abramov Glacier after 2009 between the constrained and unconstrained model?

2009 was a rather cold and snow-rich year. Especially summer snowfall reduced the melt for most glaciers in the region (Barandun et al., 2015; Kenzhebaev et al., 2017; Kronenberg et al., 2016). A less negative mass balance can be observed for all three glaciers in the results obtained from both models.

The divergence between the constrained and unconstrained model increases after 2011. SMB are much more negative for the unconstrained model from 2011 to 2016 than before. This is most likely due to the change of the meteorological input datasets. In 2011, the new meteorological station was installed, and we replaced the Reanalysis temperature data with measured air temperature. With the use of the snowline data the change of the meteorological data is secondary because of the decreased sensitivity towards the meteorological input. However, when using an unconstrained model, such effects can be quite large as shown in Figure 12.

22-15: The TSL observations also represent a direct point balance observations of considerable value.

We agree with the reviewer. However, the use of the transient snowline as point mass balance observation is not the focus of this paper and we prefer not to provide more details on this subject here in order to keep our article focussed.

23-9: Consult and refer to Bazhev (1973) who directly measured the internal accumulation in firn on a glacier in the Pamirs and Abramov glacier. Found that almost all meltwater refroze in upper four layers of firn and the amount was in the 0.20 m/a range, this supports the approached used here. Further it is worth mentioning that such a study of internal accumulation should be redone some year as part of the mass balance program. Miller and Pelto (1999) observed a reduction in internal accumulation, on Lemon Creek Glacier, Alaska which if it occurs has impacts on the energy balance.

For the estimate by Barandun et al. (2015) from where we adopted the estimate of internal accumulation, the study by Bazhev (1973) was used for calibrating the refreezing model. In Barandun et al. (2015), the quantification of refreezing is based on calculating a temperature profile in firn and ice using the heat conduction equation (see, (e.g. Pfeffer et al., 1991)). The refreezing model is calibrated by adjusting firn temperature at the bottom of the profile at model initialization to match repeated firn temperature measurements made in three firn cores (Glazirin et al., 1993). The results were finally compared to findings for Abramov presented by Bazhev (1973).

During recent field visits, we measured firn temperature at two locations in the accumulation zone. No negative temperatures during summer field campaign where found indicating that all energy available for refreezing melt water had been used. A new project (since April 2017) aims at analysing the firn stratigraphy, and at quantifying of refreezing on Abramov Glacier. However, no results are available yet. We thus decided not to add more information on the calculated internal balance but refer to published former work.

Figure 12: I do not think this is needed, if included redesign as the visual message is not well communicated by the approach used.

We would like to keep the figure in the manuscript. We are nevertheless very open for suggestions to better communicate the visual message.

25-12: Worth noting that a SCAF time series such as in Figure 5 is also a critical value for water resource modelling, because of the different DDFs and DDFi values.

We agree that the method carries a large potential to retrieve mass balance information at higher temporal scale that might be useful for water resource management. However at the moment, the uncertainties related to the daily mass balance series are high and we prefer to refer only to the annual balance components (see also comments above).

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Multi-decadal mass balance series of three Kyrgyz glaciers inferred from ~~transient~~ modelling constrained with repeated snowline observations

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Abstract.

Glacier surface mass balance observations in the Tien Shan and Pamir mountains are sparse and often discontinuous. Nevertheless, glaciers are one of the most important components of the high-mountain cryosphere in the region ~~;~~ as they strongly influence water availability in the arid, continental and intensely populated downstream areas. This study provides reliable and continuous surface mass balance series for selected glaciers located in the Tien Shan and Pamir-Alay. ~~A combination~~ By cross-validating the results of three independent methods~~was used to reconstruct for the past two decades the~~, we reconstructed the mass balance of the three benchmark glaciers, Abramov, Golubin and ~~No. 354.~~ Glacier No. 354 for the past two decades. By applying different approaches, it was possible to compensate for the limitations and shortcomings of each individual method. This study proposes the use of transient snowline observations throughout the melting season obtained from satellite optical imagery and terrestrial automatic cameras. By combining modelling with remotely acquired information on summer snow depletion, it was possible to infer glacier mass changes for unmeasured years. Multi-annual mass changes based on high-accuracy digital elevation models and in situ glaciological surveys were used to validate the results for the investigated glaciers. Substantial surface mass loss was confirmed for the three studied glaciers by all three methods, ranging from -0.30 ± 0.19 m w.e. ~~a~~yr^{-1} to -0.41 ± 0.33 m w.e. ~~a~~yr^{-1} over the 2004-2016 period. Our results indicate that integration of snowline observations into mass balance modelling significantly narrows the uncertainty ranges of the estimates, ~~and hencehighlights~~ hence, highlighting the potential of the methodology for application to ~~inaccessible~~ unmonitored glaciers at larger scales for which no direct measurements are available.

1 Introduction

Glaciers are important components of the hydrological cycle in Central Asia. In this arid continental region, the intensely populated and irrigated downstream areas strongly depend on a supply of water from the cryosphere such as glaciers and snow ~~(Kaser et al., 2010; Schaner et al., 2012; Duethmann et al., 2014; Chen et al., 2016; Huss et al., 2017)~~(Kaser et al., 2010; Schaner et al., 20 . The uncertainty of water availability in the context of a changing climate creates a major potential for political tension and builds a complex set of future threats, affecting different sectors such as water management, energy production and irrigation (Varis, 2014; Munia et al., 2016; Pritchard, 2017). Climate change poses a manifold challenge for the Central Asian population and will influence natural hazards and threaten future economies and the livelihood of coming generations ~~(IPCC Climate Change, 2013)~~(Stocker et al., 2013). For this reason, continuous and high-quality data for the different components of the hydrological cycle acquired within established regional and national cryospheric and hydrologic climate services are key for providing accurate predictions which enable sustainable adaptation. As stated by the World Meteorological Organization (GCOS, 2016), large gaps currently exist in the global climate observation system. This refers in equal measure to such remote and ~~inaccessible areas ,~~ unmonitored areas as the Pamir and the Tien Shan, where there is a lack of data crucially needed to plan and enhance future development (Sorg et al., 2012; Unger-Shayesteh et al., 2013). Improved temporal and spatial representation of glacier monitoring is thus essential, due to the paramount ~~signification~~ significance of glaciers in the high-mountain cryosphere.

During the Soviet era, in the 1950s and 1960s, an extensive system of cryospheric monitoring was launched in the Tien Shan and Pamir~~region~~. Most programmes stopped abruptly with the breakdown of the USSR in the mid-1990s. Monitoring activities were maintained only on Tuyuksu Glacier, Kazakhstan, and Urumqi Glacier (No. 1), China. In recent years, different initiatives have aimed at the re-establishment of glacier monitoring in Central Asia (Hoelzle et al., 2017). ~~Mass balance~~ Surface mass balance (SMB) series are now available for the following glaciers: Abramov (Pamir-Alay), Batysh Sook, Sary-Tor, Karabatkak and Glacier No. 354 (Central Tien Shan), for ~~Urumchi~~ Urumqi No. 1 (Eastern Tien Shan) and for Golubin and Tuyuksu (Northern Tien Shan) (Fig. 1) (WGMS, 2013). However, a significant gap in the data from the mid-1990s to around 2010 hinder the interpretation of long-term trends in glacier behaviour in this region.

Different studies derived continuous mass balance series for selected glaciers based on modelling ~~(e.g.,, Fujita et al., 2011; Barandun et a~~ (e.g., Fujita et al., 2011; Barandun et al., 2015; Kronenberg et al., 2016; Liu and Liu, 2016; Kenzhebaev et al., 2017) and estimated mass balance at a regional scale in the Pamir-Alay and Tien Shan (Farinotti et al., 2015). Modelled mass balance series have a good temporal resolution; however, they are not observation-based and thus strongly depend on model calibration and the quality of the input variables. Several studies use remote sensing techniques to fill the gaps in glacier monitoring and to generate insights into region-wide mass changes covering entire High Mountain Asia within the past two decades ~~(e.g., Gardner et al., 2013; Gardelle et al., 2013; Kääb et al., 2015; Brun et al., 2017; Wang et al., 2017)~~(e.g. Gardner et al., 2013; Gardelle . Furthermore, other authors focused on selected regions of the Central and Northern Tien Shan (e.g., Aizen et al., 2007; Pieczonka et al., 2013; Bolch, 2015; Pieczonka and Bolch, 2015; Goerlich et al., 2017) deriving glacier-specific geodetic mass balances. These studies often cover large areas, but temporal resolution is typically limited to five years or longer periods. Thus, they fail to capture the interannual or even seasonal signals.

The snowline is recognized as a valuable proxy for glacier mass balance (LaChapelle, 1962; Lliboutry, 1965; Braithwaite, 1984; Kulkarni, 2012; Rabatel et al., 2017). Different methods have been developed to use the end-of-summer snowline observed on air- and spaceborne data, i.e., without direct access to the glacier, to infer glacier mass changes based on a statistical relation between the equilibrium line altitude and the glacier-wide ~~mass balance~~ SMB (e.g., Kulkarni, 1992; Dyurgerov, 1996; Rabatel et al., 2005). These methods were applied to glaciers located in a wide range of different regions, such as in Europe (e.g., Hock et al., 2007; Rabatel et al., 2008, 2016), South America (e.g., Rabatel et al., 2012), New Zealand (e.g., Chinn, 1995, 1999), the Arctic (e.g., Mernild et al., 2013), the Himalayas (e.g., Kulkarni et al., 2004, 2011) and Central Asia (e.g., Dyurgerov et al., 1994; Kamniansky and Pertziger, 1996). Some pioneer studies (e.g., Østrem, 1973, 1975; Young, 1981; Dyurgerov et al., 1994) have identified the value of transient snowline (TSL) observations in connection with sub-seasonal ~~mass balances~~SMB. Recent studies ~~(e.g., Hock et al., 2007; Pelto, 2010, 2011; Huss et al., 2013; Hulth et al., 2013)~~ (e.g., Hock et al., 2007; Pelto, 2010; Pelto et al., 2013; Huss et al., 2013; Hulth et al., 2013) have further developed this concept to improve surface mass balance monitoring and modelling strategies, including information extracted from continuous ~~snowline~~ TSL observations. However, most approaches still rely on long-term glaciological information and are thus not applicable to ~~inaccessible~~ unmonitored glaciers located in remote and unmeasured regions.

In this study, three pillars of a multi-level strategy for glacier observation are combined, covering the period of the past two decades, to improve the understanding of mass change evolution of Abramov, Golubin ~~Glacier~~ and Glacier No. 354, ~~the~~ three benchmark glaciers in the Tien Shan and Pamir-Alay. (1) We integrate in situ glaciological measurements, when available, to compute annual ~~mass balances~~ SMB using a model-based extrapolation of the measurement points to reach glacier-wide coverage. (2) We calculate geodetic mass changes based on high-resolution digital elevation models (DEMs) on decadal to semi-decadal time scales. (3) We infer daily ~~mass balance~~ SMB series using a model approach supported by transient snowline observations, as a proxy for glacier mass balance. In this way, a ~~temperature index~~ temperature-index model is calibrated with the snow-covered area fraction (SCAF) of the glacier observed on satellite optical imagery and time-lapse photographs throughout the ablation season. This approach represents a new tool for glacier observation at high temporal and spatial resolution. The remote snowline observations provide valuable information, especially for periods for which no direct measurements are available. By combining different independent approaches, we aim to overcome the limitations and shortcomings of each individual method and to deliver a robust mass balance estimate for the three selected glaciers ~~with high temporal~~ at annual resolution for a period for which only limited data has been available so far.

2 Study Site and Data

2.1 Study sites

In this section we present a brief overview of the study sites. A detailed description of the three selected glaciers and their geographic and climatological settings is given in Hoelzle et al. (2017). Table 1 summarizes the available data for each glacier.

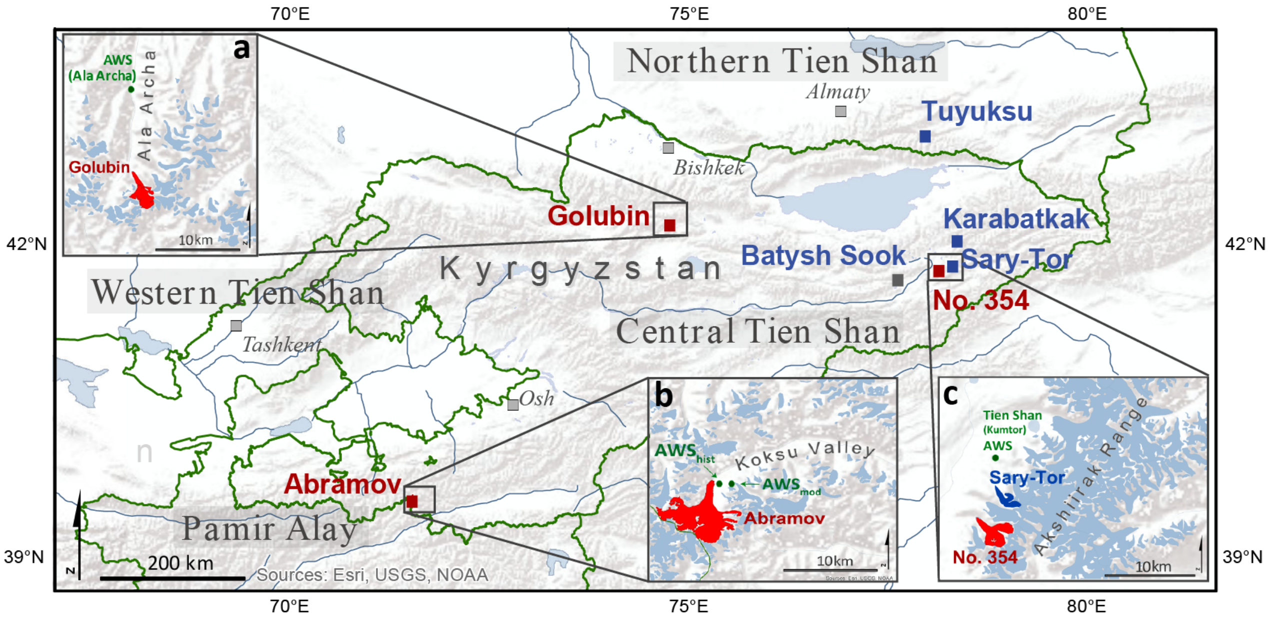

Figure 1. Overview map of Central Asia showing the location of glaciers (blue) with available long-term ~~mass balance~~ SMB measurements. Glaciers investigated in this study are marked in red. The insets show the position of the automatic weather station (AWS) for (~~a~~**a**) Golubin, (~~b~~**b**) Abramov and (~~c~~**c**) Glacier No. 354. Note that AWS~~$_{mod.}$~~$_{mod}$ indicates the position of the new AWS installed in 2011 and AWS~~$_{hist.}$~~$_{hist}$ the ~~location of the~~ old glaciological station at Abramov.

2.1.1 Abramov Glacier

Abramov Glacier (N 39°36.78′, E 71°33.32′) is located in the Pamir-Alay (North-Western Pamir, Fig. 1). The north to north-east facing glacier has an extent of about 24 km^2 (as of 2016) and ranges from 3650 m a.s.l. to nearly 5000 m a.s.l. Barandun et al. (2015) suggested that the glacier had a mean annual balance of -0.44 ± 0.10 m w.e. ~~a~~yr^{-1} between 1968 and 2014 and estimated internal accumulation and basal ablation to contribute by $+0.07$ m w.e. ~~a~~yr^{-1} to the total mass change of the glacier. A recent study by Brun et al. (2017) indicates a mass loss of -0.38 ± 0.10 m w.e. ~~a~~yr^{-1} for Abramov from ca. 2002 to 2014.

Mean daily air temperature and total daily precipitation sums were measured at a glaciological station located at 3837 m a.s.l. from 1967 to 1998 (Fig. 1). The station was located at a distance of about 0.5 km from the glacier tongue. Air temperature measured at an Automatic Weather Station (AWS$_{mod}$) ~~installed in 2011~~ was used from 2011 to 2016 (Fig. 2a). This station is located at an elevation of 4100 m a.s.l. at a distance of about 1.5 km from the glacier terminus. ERA-interim Reanalysis data with spatial resolution of 0.78 degrees (Dee et al., 2011) were used to fill measurement gaps (Barandun et al., 2015).

The ~~glacier mass balance~~ SMB was measured intensively from 1967 to 1998 (Suslov et al., 1980; Glazirin et al., 1993) and the monitoring was re-established in 2011 (Hoelzle et al., 2017). Since then, annual glaciological surveys were continuously carried out in late August. For a re-analyzed and reconstructed mass balance series for Abramov from 1968 to 2014 and a detailed description of the measurement network, see Barandun et al. (2015).

2.1.2 Golubin Glacier

Golubin Glacier (N42°26.94′, E 74°30.10′) is located in the Ala Archa valley in the Kyrgyz Ala-Too in the Northern Tien Shan (Fig. 1). The glacier has an area of ∼5 km^2 (as of 2016) and a north to northwestern aspect. The ~~front~~ terminus is currently located at an elevation of about 3400 m a.s.l. and the glacier ~~spans~~ extends to an elevation of about 4300 m a.s.l. Long-term measurements indicated an internal accumulation due to refreezing of meltwater of about +0.08 m w.e. ~~a~~yr^{-1} (Aizen et al., 1997). For Golubin, ~~mass loss was~~ the geodetic mass loss reported by Bolch (2015) ~~and Brun et al. (2017) for recent decades.~~was -0.28 ± 0.96 m w.e. yr^{-1} from 2000 to 2012, whereas Brun et al. (2017) found a geodetic mass balance of -0.04 ± 0.19 m w.e. yr^{-1} for the period 2002 to 2013.

We used meteorological data from the Alplager station located in the Ala Archa valley, situated at an elevation of 2145 m a.s.l. at a distance of about 10 km from the glacier (Fig. 1). There are several other meteorological stations in the valley, however, the Alplager station has the most complete and continuous series at high elevation covering the entire study period.

Intense glacier monitoring started in 1958 and continued until 1994 when the monitoring programme was stopped (Aizen, 1988). In summer 2010, ~~mass balance~~ SMB measurements were re-initiated. Figure 2b summarizes the monitoring network at Golubin ~~Glacier~~ as of 2016, including a ~~mass balance~~ SMB measurement network, an AWS (≈3300 m a.s.l.) and two terrestrial cameras installed in 2013. A detailed description of the monitoring strategy is provided in Hoelzle et al. (2017).

2.1.3 Glacier No. 354

Glacier No. 354 (N 41°47.62′, E 78°9.69′) is situated in the Akshiirak range in the Central Tien Shan (Fig. 1). The glacier covered a surface area of about 6.4 km^2 in 2016. The accumulation zone comprises three basins and the glacier tongue is oriented to the northwest. The glacier spans an elevation range of 3750-4680 m a.s.l. Mass loss since the mid-1970s was reported by different studies ranging from about -0.8 to -0.5 m w.e. yr^{-1} (Pieczonka and Bolch, 2015; Kronenberg et al., 2016; Brun et al., 2017). Summer snowfall is frequent and fresh snow can cover the entire glacier surface for several days during the melt season, significantly reducing ablation (Kronenberg et al., 2016). Evidence of persistent superimposed ice is found and Kronenberg et al. (2016) estimated internal accumulation to be +0.04 m w.e. ~~a~~yr^{-1}. An AWS (Tien Shan (Kumtor) AWS) installed at ~~a~~ an elevation of ≈3660 m a.s.l. and a distance of approximately 10 km to the glacier ~~records~~ recorded continuous meteorological data for the study period (Fig. 1). We used daily precipitation sums and mean daily air temperature for modelling.

Since 2010, in situ ~~mass balance~~ SMB has been obtained annually in late summer (Fig. 2c). Winter measurements exist for May 2014 (Kronenberg et al., 2016). A description of the meteorological input data and the ~~mass balance~~ SMB measurement network, as well as a reconstruction of the mass balance series back to 2003 are provided ~~in~~ by Kronenberg et al. (2016).

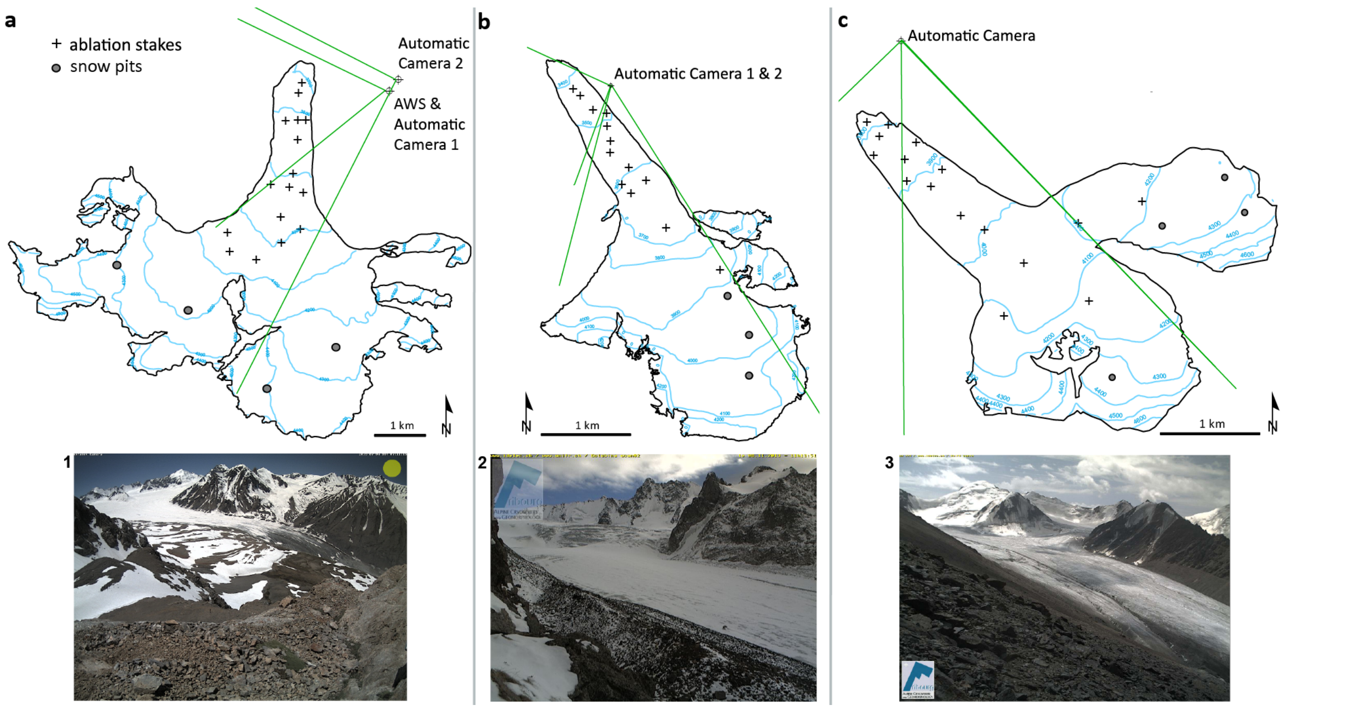

Figure 2. Glacier monitoring network at (~~A~~**a**) Abramov~~Glacier~~, (~~B~~**b**) Golubin ~~Glacier~~ and (~~C~~**c**) Glacier No. 354. A photograph taken by the terrestrial cameras is shown for (~~1~~**1**) Abramov, (~~2~~**2**) Golubin and (~~3~~**3**) Glacier No. 354.

2.2 High-resolution satellite images and DEMs

To compute geodetic mass balances for Abramov~~Glacier~~, high-resolution DEMs were used based on Pléiades ~~data~~ stereo images acquired in 2015, and on stereo images from 2003 and 2011 from Satellite Pour l'Observation de la Terre (SPOT) 5. For Glacier No. 354, DEMs from 2003 (QuickBird) and from 2012 (GeoEye) were available from Kronenberg et al. (2016). In addition, a SPOT6 stereo-pair acquired in 2015 was used to produce an updated DEM. High-resolution images for Golubin ~~Glacier~~ are sparse and we had to rely on a SPOT7 tri-stereo scene from November 2014 and on Advanced Land Observing Satellite (ALOS) Prism scenes from 2006 (Table 1). Important snow coverage was present on the SPOT5 image from 2011 for Abramov and on the SPOT7 image from 2014 for Golubin. A fine layer of fresh snow covered parts of the SPOT6 image from 2015 for Glacier No. 354. For modelling purposes, the most complete and accurate DEM available of each glacier was used to represent the surface topography (Table 1).

2.3 Optical satellite and terrestrial camera images

We used freely accessible, orthorectified and georeferenced Landsat TM/ETM+ and ~~OLIs~~OLI, Terra ASTER-L1B and Sentinel-2A scenes to repeatedly observe the glacier outlines and the snowline throughout the melting season for all three glaciers. In addition, we used the snow-free high-resolution optical satellite images as described above for snowline and glacier outline mapping.

Two terrestrial cameras (Mobotix M25) overlooking Abramov ~~Glacier~~ were installed in August 2011. One camera was located next to the $\mathrm{AWS_{mod}}$, and the other one at approximately 500 m distance at an elevation of 4200 m a.s.l. (Fig. 2a). Due to multiple camera failures and power supply problems, pictures were lacking from the end of the ablation season in 2012 to the end of the ablation season in 2013, and again partly for the summer months in 2014. In 2015, continuous coverage was obtained from Camera 1 but only a few images could be retrieved from Camera ~~2 (Fig. 2a).~~ 2. A complete set of data was collected from both cameras for the first time in 2016. A similar setup has been installed for Glacier No. 354 in 2014, delivering continuous coverage since implementation (Fig. 2c). The camera is located at an elevation of 4145 m a.s.l. Images from the two cameras installed at Golubin were not used here due to limited image quality ~~.~~ (Fig. 2b). Figure 3 illustrates the number of camera and satellite images with satisfying quality that were used to obtain maps of snowlines for the three glaciers. Image availability for snowline mapping prior to 1998 was insufficient for the most part~~insufficient~~.

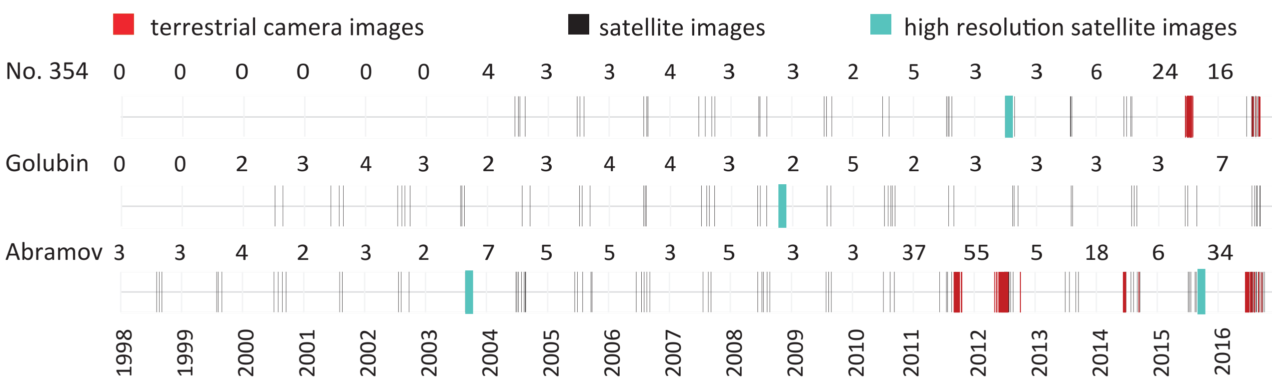

Figure 3. Image availability and distribution for snowline mapping. Numbers indicate the total available scenes per year and glacier. Prior to 1998, image coverage is sparse for all three glaciers. For Golubin and for Glacier No. 354, the first summer season for which enough snowline observations could be collected was 2000 and 2004, respectively. Snow-covered high-resolution images have not been used to delineate the snowline and are not shown here.

3 Methods

3.1 Glacier outlines

Glacier extents were mapped manually based on satellite images for all three glaciers and for each year of the corresponding study period. Only cloud- and snow-free images were selected. The surfaces of Glacier No. 354 and Golubin ~~were~~ are mostly debris-free. We excluded a debris-covered part ~~, due to~~ with strongly reduced melt rates ~~,~~ at the western margin of Abramov

Table 1. Available data on glacier monitoring for the three glaciers used in this study. The dates marked with an asterisk indicate the DEMs used as a topographic base for the modelling.

	Abramov	Golubin	Glacier No. 354
No. surface mass balance measurements per year	22	14	16
No. annual glaciological surveys (~~2000 – 2016~~2000-2016)	5	6	6
Total No. ~~SNL~~ snowline observations	122	56	78
High-resolution satellite stereo images	27/08/2003 (SPOT5)	08/09/2006 (ALOS)*	01/09/2003 (QuickBird)
	29/11/2011 (SPOT5)	01/11/2014 (SPOT7)	27/07/2012 (GeoEye)*
	01/09/2015 (Pléiades)*		01/10/2015 (SPOT6)

~~Glacier~~ (Barandun et al., 2015). Annually repeated ~~glacier front measurements~~ measurements of the glacier front position using a handheld GPS for all three glaciers were ~~included also~~ combined with the satellite observations for mapping from 2011 ~~onwards~~onward. The same extents were used for all three methods. Errors related to glacier outlines digitized manually on remote sensing images depend on atmospheric and topographic corrections, shading, glacier surface characteristics, snow cover and local clouds, but mainly on misinterpretation of debris cover (Paul et al., 2013, 2015). Uncertainties are expected to be in the range of $\pm5\%$ of the total glacier area for low-resolution images, and smaller for high-resolution images (Paul et al., 2013).

3.2 Meteorological data

For Abramov~~Glacier~~, the air temperature data measured at the AWS was adjusted to the elevation of the former glaciological station by applying a constant lapse rate of $-6\,^{\circ}\mathrm{C\,km^{-1}}$ (Suslov et al., 1980). The ERA-interim Reanalysis dataset was adapted by applying mean monthly additive and multiplicative biases for air temperature and precipitation, respectively. The biases were calculated from long-term in situ measurements (Barandun et al., 2015). From the corrected monthly means, daily series were generated by superimposing day-to-day variability, observed at the meteorological station from 1969 to 1994. For Abramov, we generated air temperature series from 1995 to 2011 and precipitation series from 1995 to 2016. More detailed information on data preparation and their suitability is given in Barandun et al. (2015).

Mean daily air temperature data measured at the Ala Archa AWS and Tien Shan (Kumtor) AWS were extrapolated to the median elevation of the corresponding glacier with monthly temperature lapse rates for the Northern and Central Tien Shan provided in Aizen et al. (1995).

3.3 Snowline delineation

A visual pre-selection of suitable camera and satellite images was taken in order to preclude problems associated with image quality such as fresh snowfall, extensive cloud cover, among others. Oblique ground-based photographs were first corrected automatically for lens distortion, then projected and orthorectified following Corripio (2004). Every pixel on the photograph was associated to the elevation of the DEM. Georeferenced products of satellite scenes were downloaded. On each camera and satellite image, the snow-covered area was digitized manually by means of visual separation of bare ice and snow ~~(Huss et al., 2013; Barandun et al., 2015; Kronenberg et al., 2016)~~(Pelto et al., 2013; Mernild et al., 2013; Huss et al., 2013). Manual detection allowed the ~~observers~~ observer's knowledge of the ~~snow cover~~ snow-cover depletion patterns to be integrated, and was assumed to be less error-prone than an automatic classification (Huss et al., 2013; Rabatel et al., 2013).

Errors occurred due to the pixel size of the images, slope of the terrain, the accuracy of the georeferencing and the quality of the DEM (Rabatel et al., 2012). In view of the fact that the border between ice and snow is not a clearly defined line, operator expertise is desired and beneficial. Contrast becomes rather weak, especially when the snowline rises above the firn line (Rabatel et al., 2013; Wu et al., 2014) for both satellite and terrestrial camera images. In order to estimate the influence of ambiguous transition areas, we conducted extensive experiments on the interpretation of the surface type (see Section 4).

We assumed the spatial depletion pattern to be approximately constant in time so that camera and satellite images with minor invisible sections of the snowline due to shading, cloud cover, Landsat 7 SLC-off void-stripes or due to the terrestrial camera view angle could be included. To fill in those data gaps, we extrapolated the snowline based on information from repeated snowline observations of images with good quality over a ≈15-year period. The effect of a misinterpretation of the snowline on the calculated ~~mass balance~~ SMB was investigated in detail and is described in Section 4.

3.4 Glaciological surface mass balance

Ablation stakes are distributed over the entire ablation zone in order to provide an optimal representation of melt patterns (Fig. 2). Each year, they are re-drilled at the initial position. An ice density of $900\,\mathrm{kg\,m^{-3}}$ was assigned. Snow pits were dug to the previous end-of-summer horizon to measure snow density and snow accumulation. Annual field surveys ranged from late July to late August and for logistic reasons, can vary from year to year. Winter snow measurements were carried out to retrieve a detailed snow distribution pattern, and to compute the winter balance for Glacier No. 354 and Golubin in May 2014 (Kronenberg et al., 2016). Winter surveys from 1993 and 1994 were available for Abramov (Pertziger, 1996). A model-based spatial extrapolation of point measurements to the entire glacier surface after Huss et al. (2009) was used to retrieve glacier-wide ~~mass balances~~ SMB for all years with direct measurements. The model is a combined distributed accumulation (Huss et al., 2008) and ~~temperature index melt model~~ temperature-index melt model with daily resolution (Hock, 1999) which was automatically optimized to best represent all collected point ~~measurements~~ data from each seasonal/annual survey. The model is considered as a suitable tool to extrapolate the glaciological point measurements to the glacier surface for the measurement periods.

3.5 Geodetic mass balance

For Abramov~~Glacier~~, the 4-m Pléiades DEM from 1 September 2015 was used as reference. It was created using the AMES stereo-pipeline (Shean et al., 2016) and the processing parameters that were used in Marti et al. (2016). The two SPOT5 DEMs (August 2003 and November 2011) were derived from High Resolution Stereoscopic (HRS) images by the French mapping

Table 2. Survey period of glaciological measurement for each glacier and each year

	?Abramov	?Golubin	?Glacier No. 354
		?10/09/2010–17/08/2011	?05/09/2010–12/08/2011
	?26/08/2011–22/08/2012	?17/08/2011–29/08/2012	?12/08/2011–14/08/2012
‘=,?=0?to	?22/08/2012–15/08/2013	?29/08/2012–25/08/2013	?14/08/2012–23/07/2013
	?15/08/2013–18/08/2014	?25/08/2013–17/08/2014	?23/07/2013–03/09/2014
	?18/08/2014–27/08/2015	?27/08/2014–09/08/2015	?03/09/2014–14/08/2015
	?27/08/2015–01/08/2016	?09/08/2015–14/09/2016	?14/08/2015–29/08/2016

agency (Korona et al., 2009). The steps required to adjust the two SPOT5 DEMs horizontally and vertically to the Pléiades reference DEM are similar to the ones followed in a previous study on the Mont Blanc area (Berthier et al., 2014).

We created DEMs with a spatial resolution of 5 m for Golubin and Glacier No. 354 from the available two/tri-stereo pairs of high-resolution satellite imagery using standard procedures and the software PCI Geomatica (Kronenberg et al., 2016). The two/tri-stereo pairs were connected using common tie points before DEM extraction. For Glacier No. 354, a horizontal shift between the two DEMs was corrected through a DEM co-registration procedure as proposed by Nuth and Kääb (2011). For the data covering Golubin, no horizontal shift was encountered. We thus corrected only for a mean elevation difference of ~~2.7~~3.9 m detected over stable ground. For this vertical co-registration, only terrain sections with a slope ~~lower than approximately~~ smaller than 30 ° were selected and areas with parallax-matching problems ~~or significant snow cover~~ were avoided. Snow-covered areas were included in the offset correction, in order to correct for fresh snow on the image, assuming similar snow thicknesses on- and off-glacier. The vertical accuracy was thus improved, and the mean absolut difference off-glacier was limited to 1.0 m (2003-2015) and 0.6 m (2011-2015) for Abramov, 0.7 m for Glacier No. 354 and 1.6 m for Golubin (see also Section 4). Steep mountain walls and shading caused problems. Areas affected ~~by these problems~~ were manually masked out. Unmeasured areas (Abramov: 26% in ~~2003–2015~~2003-2015, and 23% in ~~2011–2015~~2011-2015; Golubin: 30%; ~~Gl.~~ Glacier No. 354: 25%) were assumed to have experienced the same elevation change as the measured areas in the same altitude band and the median of the corresponding elevation bin was used for gap-filling. For elevation bins higher than 4300 m a.s.l. at Golubin (9% of total area) and for elevation bins higher than 4500 m a.s.l. at ~~Gl.~~ Glacier No. 354 (8% of total area), obvious DEM errors ~~dominated~~ were dominant and not enough realistic values for median elevation-change calculation were available. ~~There~~Thus, the median of the uppermost elevation band with reliable data was used to fill in the gaps. To derive the geodetic mass balance ΔM_{geod}, a density $\rho_{\Delta \mathrm{V}}$ of 850 kg m^{-3} was used for volume-to-mass conversion (Huss, 2013):

$$\Delta M_{\mathrm{geod}} = \frac{\Delta V \cdot \rho_{\Delta \mathrm{V}}}{\overline{A} \cdot \Delta t} \tag{1}$$

where, $\overline{A}$ is the average glacier area and Δt is the time in years between the corresponding image pairs. Uncertainties in the detected elevation changes and the derived geodetic mass balances are described in Section 4.

3.6 ~~Mass~~ Surface mass balance modelling constrained by snowline observations

An accumulation and ~~temperature index~~ temperature-index melt model closely constrained by transient snowline observations was implemented in order to infer glacier-wide ~~mass balance~~SMBs. The applied methodology is a further stage in the approach presented by Huss et al. (2013). The principle of the approach is to employ the information given by the temporal change in the position of the transient snowline throughout the ablation season to constrain both the amount of winter snow accumulation and melting by iteratively calibrating a mass balance model. ~~Thus the daily mass balance evolution through each individual year can be inferred.~~ The approach also allows us to temporally extend ~~mass balance~~ SMB estimates to the end of the hydrological year although snowline observations do not cover the entire ablation season. The methodological steps are described in more detail in the following.

A surface mass balance model with a spatial resolution of 20 m was driven with daily mean air temperature and precipitation sums measured at nearby meteorological stations or inferred from Reanalysis data (see Section 2.1). We used a classical ~~temperature index~~ temperature-index melt model (e.g., Braithwaite, 1995; Hock, 2003). Melt M was calculated for each grid cell x, y and time step t based on a linear relation with positive daily mean air temperature $T_{\mathrm{air}}(x,y,t)$ as

$$M_{x,y,t} = \begin{cases} DDF_{\mathrm{ice/snow}} \cdot T_{\mathrm{air(x,y,t)}} & T_{\mathrm{air}} > 0^{\circ} \\ 0 & T_{\mathrm{air}} \leq 0^{\circ} \end{cases} \tag{2}$$

Daily air temperatures are extrapolated to each grid cell using a constant temperature lapse rate based on literature values (Table 3). Different degree-day factors $DDF_{\mathrm{ice/snow}}$ were chosen for snow and ice surfaces. The surface type over the glacier area was given by the snow depth updated with modelled daily snowfall and melt. The ratio between DDF_{ice} and DDF_{snow}, R_{DDF}, was held constant over time. As a wide range of different ratios can be found in literature ~~(e.g., Hock, 2003; Zhang et al., 2006; Gao et al., 20~~ (e.g., Hock, 2003; Zhang et al., 2006; Gao et al., 2010; Liu and Liu, 2016), we decided to constrain R_{DDF} by ~~mass balance~~ SMB measurements in the Tien Shan and Pamir (Table 3). A sensitivity test shows that a variation of R_{DDF} by $\pm 25\%$, a value exceeding the maximum range found in the literature ($\pm 22\%$), only causes small changes in modelled ~~mass balance~~ SMB (Table 4) indicating that ~~the calibrated~~ calibrating R_{DDF} improves model performance to some extent but is not essential to applying the model. For more details see Section 4.

Snow accumulation C was calculated for each grid cell x, y and time step t by

$$C_{(x,y,t)} = P_{\mathrm{ws}}(x,y,t) \cdot C_{\mathrm{prec}} \cdot (1 + (z_{(x,y)} - z_{\mathrm{ws}}) \cdot \delta P/\delta z), \tag{3}$$

where P_{ws} is the measured precipitation at the meteorological station at elevation z_{ws}. $z(x,y)$ is the elevation of each grid cell. The measured precipitation was extrapolated to every grid cell with a constant precipitation gradient $\delta P/\delta z$ calculated from winter snow surveys (Table 3). Solid precipitation occurs at $T_{\mathrm{air}} \leq 1.5\,{}^{\circ}C$ with a linear transition range of ± 1°C (e.g., Hock, 1999). C_{prec} is a scaling factor that accounts for gauge under-catch and other systematic measurement errors of precipitation (e.g., Huss et al., 2009). In order to account for smaller measurement errors during summer related to the type of

Table 3. Constant model parameters. The temperature lapse rate for Abramov ~~Glacier~~ was adopted from Barandun et al. (2015) and for Golubin ~~Glacier~~ and Glacier No. 354 from Aizen et al. (1995). $\delta T/\delta z$, $\delta P/\delta z$, ~~H_{crit}~~ ?Z_{crit} and R_{DDF} are held constant throughout the ?entire modelling period. ~~H_{crit} is the elevation where precipitation is set to no longer increase linearly.~~ The initial parameter ranges of DDF_{snow} and C_{prec} as well as the mean value obtained from annual calibration is given with its standard deviation.

parameter	Abramov	Golubin	?Glacier No. 354	unit
$\delta T/\delta z$	-4.8	-6.3	-6.7	$^{\circ}\mathrm{C\,km^{-1}}$
$\delta P/\delta z$	6.4	4.5	1.5	$\%\,10^{-4}\,\mathrm{m^{-1}}$
R_{DDF}	1.57	1.36	1.06	–
~~H~~?$\mathrm{Z_{crit}}$	4400	4000	4500	m a.s.l
annually variable model parameters				
initial range				
DDF_{snow}	3.5 – 5.5	3.0 – 5.5	1.5 – 4.5	$\mathrm{mm\,day^{-1}\,^{\circ}C^{-1}}$
$\mathrm{C_{prec}}$	1.75 – 3.0	1.5 – 3.0	1.0 – 3.5	–
best combination				
DDF_{snow}	4.54 $\pm$0.74	~~5.49~~ ?5.09 $\pm$0.46	3.04 $\pm$0.66	$\mathrm{mm\,day^{-1}\,^{\circ}C^{-1}}$
$\mathrm{C_{prec}}$	2.23$\pm$0.40	1.46$\pm$0.31	2.35 $\pm$0.29	–

precipitation (solid/liquid, wet/dry snow), C_{prec} was reduced for the summer months to 25% of its value (Sevruk, 1981). Above a critical elevation ~~H_{crit}~~ Z_{crit}, precipitation is set to no longer increase linearly (Alpert, 1986). Our selected value of ~~H_{crit}~~ Z_{crit} approximated the elevation for which a decrease in accumulation was observed on long-term monitored glaciers situated in the Tien Shan and Caucasus (WGMS, 2013). ~~Parameters~~ All parameters used are summarized in Table 3.

3.6.1 Model calibration

We calibrated C_{prec} and DDF_{snow}, keeping R_{DDF} constant. C_{prec} and DDF_{snow} were calibrated annually and for each glacier separately ~~,~~ to correctly represent the winter snow accumulation and the melt rate. To calibrate C_{prec}, we relied on the fact that, at the position of the transient snowline, icemelt had not yet started but all winter snow was melted. The modelled cumulative melt, calculated at the position of the observed snowline, is thus interpreted as the total amount of accumulated winter snow that melted from the onset of the ablation season until the snowline observation date. Using the melt model, we can infer the winter accumulation at the beginning of the ablation season along each observed snowline. This quantity needs to agree with the directly modelled snow accumulation at the end of the winter season. DDF_{snow} was calibrated to best represent all SCAF observations of one ablation season (Fig. 4).

As C_{prec} and DDF_{snow} depend on each other, overestimation of DDF_{snow} could cause an overestimation of C_{prec}, and vice versa, without affecting the modelled position of the snowline and the SCAF. To overcome this problem, the values of C_{prec} and DDF_{snow} were constrained to remain within realistic bounds. Through an iterative calibration procedure, we aimed at finding the best possible parameter combination without the need of any additional information.

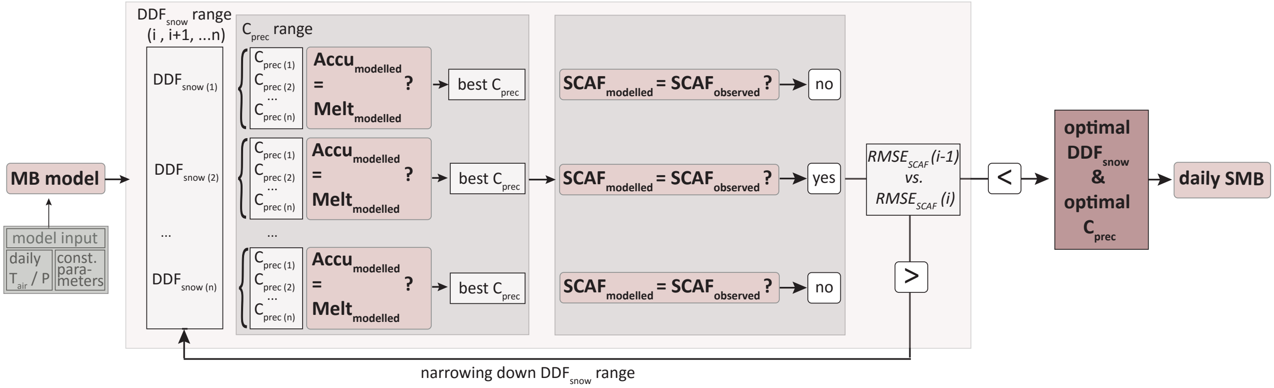

Figure 4. Calibration procedure to obtain an ideal combination of DDF_{snow} and C_{prec}. An initial range for DDF_{snow} and C_{prec} was narrowed down through comparison to snowline observations until an optimal solution for both parameters was found. First, for each initial value of DDF_{snow}, the best value of C_{prec} was determined constraining the modelled cumulative melt ($\cancel{M_{\text{modelled}}}$?$Melt_{\text{modelled}}$) at the snowline position to agree with the modelled winter snow accumulation (~~C~~?$\text{Accu}_{\text{modelled}}$) for the same location. Second, the performance of each DDF_{snow} was evaluated to narrow down the range of DDF_{snow} by comparing ?the $\text{RMSE}_{\text{SCAF}}$ of the modelled and observed snow-covered area fractions (SCAF). This was repeated until an optimal solution is reached.

First, we defined a plausible range for DDF_{snow} and C_{prec} for all three glaciers based on literature (Hock, 2003; Liu and Liu, 2016) (Table 3). For each DDF_{snow}, an optimal parameter C_{prec} was calibrated through iteratively narrowing a plausible range of initial values of C_{prec} (Fig. 4). In this way, the RMSE between the directly modelled winter snow accumulation $\cancel{C_{\text{modelled}}}$ $Accu_{\text{modelled}}$ and the modelled cumulative melt from the onset of the ablation season to each observation date $\cancel{M_{\text{modelled}}}$ $Melt_{\text{modelled}}$ was minimized until no further improvement of the RMSE was observed.

Second, the performance of each DDF_{snow} with its optimal C_{prec} pair, was evaluated based on the $\text{RMSE}_{\text{SCAF}}$ between the observed $SCAF_{\text{obs}}$ and the modelled $SCAF_{\text{modelled}}$ for all available snowline observations within one year (Fig. 4). The range of DDF_{snow} was narrowed around the best solution and the optimization process was restarted until no further significant improvement of the $\text{RMSE}_{\text{SCAF}}$ was observed. The calibration procedure was repeated for each year individually.

A minimum of two images was needed to enable application of our calibration approach. The influence of the image frequency and distribution was assessed in detail with sensitivity experiments described in Section 4. In a last step, the calibrated model was re-run with the ideal parameter set. This snowline-constrained mass balance model was thus applied to derive continuous daily ~~mass balance~~ SMB series that agreed with the snow depletion patterns observed by remote sensing imagery. In the following, we refer to the ~~results obtained by the~~ methodology described above as ~~*snowline-derived mass balance*~~*snowline approach*.

3.6.2 Adjustments to enable comparison of different methods

Geodetic surveys provide an estimate of the total mass change of a glacier ΔM_{geod}, whereas ~~snowline-derived mass balance series~~ the results inferred from the snowline approach refer to the surface ~~balance B_{a}~~ mass balance B_{sfc} and do not account for internal and basal components of the mass balance (Cogley et al., 2011). For comparing the results, we adjusted the ~~glaciological and snowline-derived surface mass balances~~ modelled SMB constrained by snowline observations, with an estimate of the internal/basal mass balance of $+0.07$ m w.e. ~~a~~yr^{-1} for Abramov (Barandun et al., 2015), $+0.08$ m w.e. ~~a~~yr^{-1} for Golubin (Aizen et al., 1997) and $+0.04$ m w.e. ~~a~~yr^{-1} for Glacier No. 354 (Kronenberg et al., 2016). Values are positive due to a significant amount of refreezing of meltwater in cold firn.

To compare the results of the different methods, the time periods covered by the datasets also needed to be homogenized. We thus adjusted the observation period of the ~~snowline-derived mass balance~~ modelled mass balance constrained by snowline observations to exactly match the respective periods of geodetic and glaciological mass balance, respectively. However, the final results ~~$B_{\mathrm{a(fix)}}$ derived from snowlines~~ $B_{\mathrm{sfc(fix)}}$ derived from the snowline approach are presented for the fixed dates of the hydrological year (1 October to 30 September) and ~~only~~ do not include internal/basal mass balance.

4 Uncertainties and model sensitivity

4.1 Glaciological surface mass balance

Uncertainty σ_{glac} related to the direct glaciological measurements for Abramov was adopted from Barandun et al. (2015), and for Glacier No. 354 from Kronenberg et al. (2016). Uncertainties concerning the ~~glaciological mass balance~~ SMB of Golubin were calculated after Kronenberg et al. (2016). Uncertainties regarding all three glaciers are summarized in Table 4 and range between 0.24 and 0.30 m w.e. ~~a~~yr^{-1}. For a sensitivity experiment we artificially shifted temperature and precipitation series used for the model-based extrapolation by ±1°C and ±25%, respectively. The resulting glacier-wide SMB indicate a very small sensitivity to the meteorological input data with a Standard Deviation (STD) of <0.01 mm w.e. yr^{-1}. We strictly refer to the annual SMB obtained for the measurement dates that are listed in table 2.

4.2 Geodetic mass balance

The total uncertainty of the geodetic mass balance ~~estimate~~ includes a random and systematic error. We followed Brun et al. (2017) for computing the random error of the ~~calculation of the random error on the~~ geodetic mass balance estimate but did not assess the systematic error. Uncertainties in elevation differences were quantified by computing the area-weighted mean of the absolute difference off-glacier in 50 m altitude bins. The resulting values for Abramov, 1.0 m for 2003-2015 and 0.6 m for 2011-2015, and for Glacier No. 354, 0.7 m for 2012-2015, are in line with the uncertainty of 1.3 m found over the Mont Blanc area through comparison of similar satellite data to elevation differences measured in situ (Berthier et al., 2014). For Golubin, a value of ~~1.8~~1.6 m indicates a slightly lower DEM quality. The uncertainty related to the density assumption for converting volume to mass change was assumed to be ±60 kg m^{-3} for time intervals larger than five years (Huss, 2013).

For shorter periods, we used a more conservative estimate of $\pm 120\,\mathrm{kg\,m^{-3}}$. The elevation uncertainty for unmeasured glacier zones was roughly estimated to be five times as large ~~than~~ as the uncertainty determined for measured locations. We assumed independence between the different error components and combined them as Root-Sum-Square (RSS) to the total uncertainty for the geodetic mass balance, σ_{geod}.

4.3 ~~Snowline-derived~~ Surface mass balance modelling constrained by snowline observations

The uncertainty introduced by the mass balance model constrained by transient snowline observations ~~σ_{snl}~~ σ_{tsl} depends on (1) the delineation accuracy of the SCAF, σ_{map}, (2) the image frequency and distribution throughout the ablation season, σ_{dis}, (3) the DEM quality, σ_{DEM}, (4) the meteorological input data, σ_{meteo}, and (5) the uncertainty in constant model parameters, σ_{para} (Table 4). The individual components were estimated as follows:

(1) The accuracy of the mapped SCAF is dependent on the positioning and the transect of the snowline, the georeferencing of the images, and the extrapolation of the snowline to invisible areas (Huss et al., 2013). The limit between snow- and ice-covered areas is often not a clear line but rather a transition zone, especially for glaciers with superimposed ice. To account for the total uncertainty related to the mapping procedure, we identified an upper- and lowermost position of the surface that could be classified as either snow or ice on each available image. Hence this zone included all ambiguous areas observed, such as cloud-covered regions, shading, superimposed ice or invisibility due to reduced image quality (e.g., Landsat 7 SLC-off void-stripes, invisible areas on photographs). We interpreted the zone to be either entirely snow-covered or entirely snow-free. The standard deviation of the minimal, maximal and optimal SCAF was used as an uncertainty. This uncertainty was calculated for each image individually. To evaluate the corresponding effects on calculated ~~mass balance~~SMB, the model was re-run with the maximal and the minimal possible SCAF. The standard deviation of the ~~mass balance~~SMB, σ_{map}, ranged between 0.06 to 0.09 m w.e. ~~a~~yr^{-1} for the three glaciers.

(2) To estimate the effect of varying image availability, we repeated the modelling using different snowline observation frequencies and temporal distributions throughout the summer for calibration. Due to limited image availability, this could only be conducted for the few years when many images were available (Fig. 3). We used the results to create a look-up table that linked the image frequency, the distribution over the ablation season and the last observation date of the season to an uncertainty estimate in the calculated annual ~~mass balance~~SMB, σ_{dis}. Tests showed that the model reacts more sensitively to ~~the~~ image distribution than to reduced image frequency (Fig. 5). A minimum of two images well distributed throughout the ablation season (i.e., at the beginning/middle and at the end) is sufficient to achieve reliable ~~mass balance~~ SMB estimates. Greater uncertainties were found if images were concentrated on, for example, a few days at the beginning of the ablation season (Fig. 5). In this case, higher image frequency cannot compensate for the missing information on the snow depletion pattern. An image taken towards the end of the ablation season is more important than images from the beginning of the summer. Our assessment of image availability resulted in smaller uncertainties for Abramov ($\sigma_{\mathrm{dis}} = 0.09$ m w.e. ~~a~~yr^{-1}) than for Golubin ~~Glacier~~ ($\sigma_{\mathrm{dis}} = 0.16$ m w.e. ~~a~~yr^{-1}) and for Glacier No. 354 ($\sigma_{\mathrm{dis}} = 0.18$ m w.e. ~~a~~yr^{-1}) (Table 4).

(3) To estimate the uncertainty caused by the DEM used for the modelling, we compared our results to those obtained from model runs that used lower-resolution DEMs. For this experiment, we replaced the high-resolution DEM with the SRTM DEM.

This enabled us to both investigate the sensitivity of the results to DEM quality and to assess our assumption of ~~the unchanged topography for the~~ unchanged topography during the entire study period. The effects of a reduced DEM quality for all three glaciers ~~are~~ were found to be small ($\sigma_{\mathrm{DEM}} < 0.03$ m w.e. ~~a~~yr^{-1}).

(4) We investigated the uncertainty related to the meteorological input data, σ_{meteo}, by re-running the model with ~~the~~ a climatological average daily temperature and precipitation series for each glacier instead of the actual meteorological series. The test assessment revealed an RMSE of 0.13 m w.e. ~~a~~yr^{-1} for the annual ~~mass balance of AbramovGlacier~~SMB of Abramov, of 0.23 m w.e. ~~a~~yr^{-1} for Golubin ~~Glacier~~ and of 0.14 m w.e. ~~a~~yr^{-1} for Glacier No. ~~354.~~ 354 (Fig. 6). These results demonstrate a relatively low sensitivity of ~~the presented model to~~ our model approach to daily meteorological input data~~and~~. With the chosen calibration procedure the model parameters DDF_{snow} and C_{prec} are adjusted to best represent the TSL observations for each year and glacier individually. The modelled SMB are thus closely tied to the snowline observations and exhibit a reduced dependence from meteorological input data. This underline the potential of our methodology for regional application based on minimal input data.

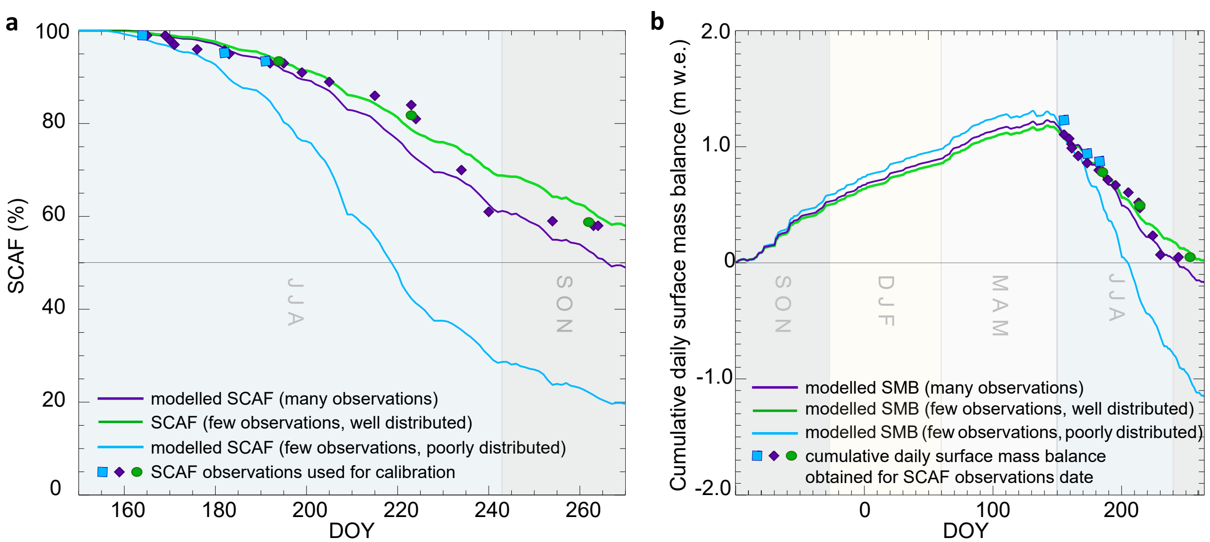

Figure 5. ?Example of the (**?a**?) daily SCAF and (**?b**?) cumulative daily SMB obtained with different sets of image frequency and distribution for Abramov in 2016. Snowline observation dates used to calibrate the model are indicated with symbols. The modelled daily SCAF and cumulative daily SMB and their corresponding snowline observations are shown with the same colour. Three images at the beginning of the ablation season (blue), three images well distributed throughout the ablation season (green), or all available images (purple) were used.

(5) To test the uncertainty introduced by the constant (i.e. uncalibrated) model parameters, $\delta T/\delta z$, $\delta P/\delta z$ and the R_{DDF} were varied by ±25% for each glacier and year. A mean standard deviation, σ_{para}, of around 0.17 m w.e. ~~a~~yr^{-1} was found. We additionally tested the behaviour of the model relative to the individual parameters and identified a higher sensitivity to $\delta T/\delta z$ and R_{DDF}, whereas sensitivities to the other parameters were minor (Table 5).

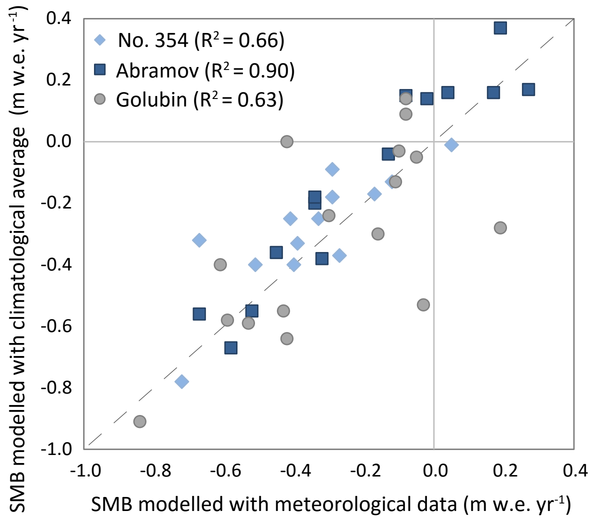

Figure 6. ?Comparison between the annual SMB obtained from the snowline-constrained model when using meteorological and climatological average daily data for Abramov (squares), Golubin (diamonds), and Glacier No. 354 (triangles).

Components 1 to 5 are assumed to be independent of each other and are combined as RSS to represent the total error of the ~~snowline-derived annual mass balance σ_{snl}.~~ annual SMB σ_{tsl} obtained from the snowline approach. We then averaged the annual error over the different periods to compute overall uncertainty.

~~Example of the (a) daily SCAF and (b) cumulative daily mass balance (modelled mb) obtained with different sets of image frequency and distribution for Abramov Glacier in 2016. Snowline observation dates used to calibrate the model are indicated with symbols. The modelled daily SCAF and cumulative daily mass balance and their corresponding snowline observations are shown with the same colour. Three images at the beginning of the ablation season (blue), three images well distributed throughout the ablation season (green), and all available images (purple) were used.~~

5 Results

5.1 Long-term ~~snowline-derived~~ surface mass balances derived from snowline approach

We found that the mass balance model constrained by snowline observations is capable of representing the observed SCAFs on satellite and terrestrial camera images within ±8% for Abramov, ~~±12%~~ ±13% for Golubin and ~~±7%~~ ±9% for Glacier No. ~~354.~~ 354 (Fig. 7). Comparing the SCAF observed on camera and on spaceborne images for the same day reveals a RMSE of 2.5%. ~~Tests~~ However, tests showed that the influence of the image source (terrestrial/space-borne) on the inferred ~~mass balance~~ SMB is negligible.

Table 4. Overall average uncertainties ~~, as well as uncertainties specified for each component~~ related to the ?three methods used, namely the glaciological σ_{glac}, geodetic ?σ_{geod} and ~~snowline-derived~~ ?snowline-constrained modelled mass balances ?σ_{tsl} for all three investigated glaciers in m w.e. ~~a~~?yr^{-1}. ?Additionally, the uncertainty for each component of the snowline approach is specified. σ_{map} shows the uncertainty of the snowline delineation, σ_{dis} the uncertainty related to image frequency and distribution, and σ_{DEM} to the DEM. σ_{meteo} indicates the uncertainty introduced by the meteorological input data and σ_{para} the one by the model parameter choice.

Uncertainty in	Abramov	Golubin	?Glacier No. 354
Glaciological SMB			
σ_{glac}	0.25	0.30	0.24
Geodetic mass balance			
σ_{geod}	0.16 (2003–15)	~~0.42~~?0.37	0.32
	0.26 (2011–15)		
SMB from snowline approach			
~~σ_{snl}~~?σ_{tsl}	0.27	0.32	0.36
σ_{map}	0.05	0.06	0.09
σ_{dis}	0.03	0.16	0.18
σ_{DEM}	0.12	0.03	0.02
σ_{meteo}	0.13	0.23	0.14
σ_{para}	0.20	0.17	0.20

Table 5. Model sensitivity to the different constant input parameters for each glacier in m w.e. ~~a~~?yr^{-1}. See text for details on the experiments.

sensitivity in	Abramov~~Glacier~~	Golubin~~Glacier~~	Glacier No. 354
$\delta T/\delta z$	0.06	0.14	0.05
$\delta P/\delta z$	0.07	0.08	0.01
R_{DDF}	0.11	0.25	0.06

Annual glacier-wide ~~, snowline-derived surface mass balance calculated for the hydrological years 1998 to 2016 for the three benchmark glaciers~~ modelled surface mass balances constrained by snowline observations, calculated for Abramov (1998-2016), for Golubin (2000-2016), and for Glacier No. 354 (2004-2016), located in the ~~Tien Shan and~~ Pamir-Alay and the Tien Shan, are predominantly negative ~~over the two last decades (Figure 8 and in~~ (Fig. 8 and Table 6). Study periods depend on the data availability for each glacier. Abramov exhibited a mean annual ~~mass balance~~ SMB of -0.30 ± 0.19 m w.e. ~~a~~yr^{-1} from 2004 to 2016. For Golubin and Glacier No. 354 a slightly more negative annual average balance of -0.41 ± 0.33 m w.e. ~~a~~yr^{-1} and -0.36 ± 0.32 m w.e. ~~a~~yr^{-1}, respectively, was calculated for the same time period (Table 6). ~~No clear mass-balance trend~~ Length change measurements underline the observed negative balance regime of all three glaciers (Hoelzle et al., 2017). A significant glacier retreat was observed for the last century. A first speed-up of frontal retreat occurred in the 1980s and acceleration was observed in the last decade. However, no clear acceleration of mass loss for the three glaciers was identified

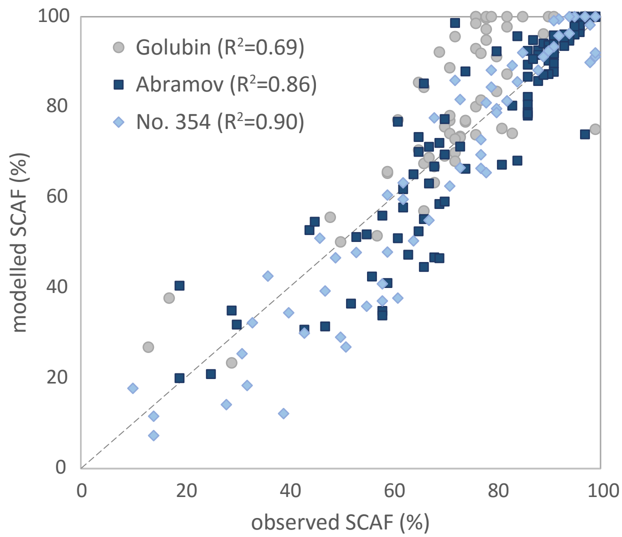

Figure 7. ?Comparison between observed and modelled SCAF for Abramov (squares), Golubin (circles), and Glacier No. 354 (diamonds).

over the investigated periods. Two phases of close-to-zero ~~mass balance~~ SMB could be recognized ~~for 2002-2004 and for~~ (2002-2005 and 2009-2011) for all glaciers. ~~Glacier No.~~ A lower standard deviation of annual mass balances from 2004 to 2016 is found for Glacier No 354 ~~, situated in a more continental climate regime, shows the weakest interannual variability and has~~ (0.19 m w.e. yr^{-1}) than for Golubin (0.4 m w.e. yr^{-1}) and Abramov (0.29 m w.e. yr^{-1}), which indicated higher interannual variability for the latter two. Glacier No. 354, receiving lower amounts of total annual precipitation, showed a smaller mass turnover and had a positive balance only in 2009 (Table 6). For Golubin ~~, on the other hand,~~ most negative values were found in 2012 and 2014. Abramov and Golubin also had strongly negative balances in 2006 and 2008. For Abramov, the snowline observations indicated that the snowline rose close to the upper edge of the glacier already at the end of August. For Golubin, observations of the last image of the season showed that the SCAF decreased to less than 45% already in mid-August in 2006, similar to 2001 and 2015. The ablation season typically stretched until the end of September, and summer snowfalls during this month were rare (Aizen et al., 1995), likely leading to continued mass loss. Data availability, however, was rather critical for Golubin in 2008, which ~~was~~ is also reflected by the ~~stronger uncertaintiesof the annual mass balance~~larger uncertainties. The last snowline observation dates from as early as the end of July.

5.2 Comparison to glaciological and geodetic mass balances

The glaciological and geodetic surveys delivered two extensive and independent datasets for validation of the ~~snowline-derived~~ modelled mass balance series constrained by snowline observations. Joint analysis of the data sets permitted robust conclusions to be drawn about the mass change and its temporal dynamics over the past two decades. The glaciological ~~mass balance~~ SMB measurements showed a good agreement with the ~~mass balance~~ SMB inferred using snowline observations for

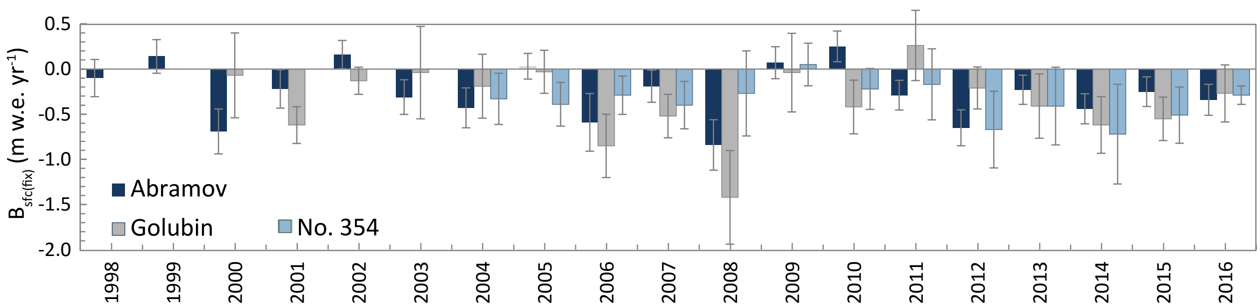

Figure 8. ?Modelled annual SMB $B_{\mathrm{sfc(fix)}}$ constrained by snowline observations for all three glaciers for the hydrological year.

the same time periods (Table 7). ~~Annual glaciological mass balances were~~ Exact survey dates are given in table 2. Annual glaciological SMB was reproduced with an RMSE of less than ±0.26 m w.e. ~~a~~yr^{-1} for all three glaciers using the snowline approach (Fig. 9). For Golubin and Glacier No. 354, the glaciological ~~mass balances~~ SMB was slightly more negative than the ~~snowline-derived balances~~ modelled SMB (Table 7). For Abramov, on the other hand, the glaciological ~~mass balance~~ SMB was somewhat less negative than the ~~snowline-derived~~ snowline-constrained model results. In general, a satisfactory agreement was obtained between the two methods for all three glaciers (Fig. 9). Squared correlation coefficients between ~~snowline-derived and glaciological mass balances between R~~snowline constrained model results and glaciological SMB ranged between r^2=0.63 (Abramov) and ~~R~~r^2=0.90 (Golubin)~~were found~~.

Table 8 and Figure 10 summarize the results obtained from the different geodetic surveys. For the comparison with the geodetic mass change, an estimate for internal/basal mass balance was added to the ~~snowline-derived surface mass balance~~ modelled SMB constrained by snowline observations (see Subsection 3.6.2) and referred to as the ~~snowline-derived~~ modelled total mass change constrained by snowline observations. The geodetic method reveals a total mass balance of $-$~~0.22~~0.30 ± ~~0.42~~0.37 m w.e. ~~a~~yr^{-1} for Golubin ~~Glacier~~ from 8 September 2006 to 1 November 2014 (Fig. 10). The corresponding total ~~snowline-derived mass balance was~~ modelled mass balance constrained by snowline observations was slightly more negative with -0.38 ± 0.35 m w.e. ~~a~~yr^{-1} for the same period ~~. However, the results of the two methods agree within their error bars~~ (Table 8 and Fig. 11). Comparison of digital elevation models indicated that Glacier No. 354 had a mass balance of -0.58 ± 0.31 m w.e. ~~a~~yr^{-1} from 27 July 2012 to 1 October 2015 (Fig. 10) and -0.42 ± 0.07 m w.e. ~~a~~yr^{-1} from 1 September 2003 to 27 July 2012 (Kronenberg et al., 2016). The total annual mass change for the same time intervals derived from the snowline approach was -0.53 ± 0.43 m w.e. ~~a~~yr^{-1} and -0.25 ± 0.31 m w.e. ~~a~~yr^{-1}, respectively. For the first period, the results are in good agreement, whereas for the second period the mass balance model constrained by snowline observations indicates a significantly less negative mass balance (Fig. 11). For Abramov, a geodetic mass balance of -0.39 ± 0.16 m w.e. ~~a~~yr^{-1} from 27 August 2003 to 1 September 2015 and of -0.36 ± 0.26 m w.e. ~~a~~yr^{-1} from 29 November 2011 to 1 September 2015 was calculated. For the same periods, the snowline model reveals a total mass change of -0.25 ± 0.20 m w.e. ~~a~~yr^{-1} and of -0.43 ± 0.17 m w.e. ~~a~~yr^{-1}, respectively. For the first period, the ~~snowline-derived mass balance~~ modelled mass balance constrained by snowline observations indicates a less negative

Table 6. Annual~~surface mass balances~~ ?, glacier-wide SMB for the three glaciers for the hydrological year ~~$B_{\mathrm{a(fix)}}$~~ ?$B_{\mathrm{sfc(fix)}}$ in m w.e?. ~~a~~?yr^{-1} ~~derived~~ ?inferred from the mass balance model constrained by snowline observations. ~~At the bottom of the table the standard deviation (STD) of the mass balance for each glacier from 2004 to 2016 is given.~~

year	Abramov	Golubin	?Glacier No. 354
1998	−0.10 ± 0.21		
1999	+0.14 ± 0.19		
2000	−0.69 ± 0.25	−0.07 ± 0.47	
2001	−0.22 ± 0.21	−0.62 ± 0.20	
2002	+0.16 ± 0.16	−0.13 ± 0.15	
2003	−0.31 ± 0.19	−0.04 ± 0.51	
2004	−0.43 ± 0.22	−0.19 ± 0.35	−0.33 ± 0.28
2005	+0.03 ± 0.14	−0.03 ± 0.24	−0.39 ± 0.24
2006	−0.59 ± 0.32	−0.85 ± 0.35	−0.29 ± 0.21
2007	−0.19 ± 0.18	−0.52 ± 0.24	−0.40 ± 0.26
2008	−0.84 ± 0.28	−1.42 ± 0.52	−0.27 ± 0.47
2009	+0.07 ± 0.18	−0.04 ± 0.43	+0.05 ± 0.24
2010	+0.25 ± 0.17	−0.42 ± 0.30	−0.22 ± 0.23
2011	−0.29 ± 0.16	+0.26 ± 0.39	−0.17 ± 0.39
2012	−0.65 ± 0.20	−0.21 ± 0.23	−0.67 ± 0.42
2013	−0.23 ± 0.16	−0.41 ± 0.36	−0.41 ± 0.43
2014	−0.44 ± 0.17	−0.62 ± 0.31	−0.72 ± 0.55
2015	−0.25 ± 0.16	−0.55 ± 0.24	−0.51 ± 0.31
2016	−0.34 ± 0.17	−0.27 ± 0.31	−0.29 ± 0.10
~~2004–2016~~ ?2004-2016	−0.30 ±0.19	−0.41 ± 0.33	−0.36 ± 0.32
~~STD 0.29 0.40 0.19~~ height			

mass balance~~. The~~ , whereas the second period is in good agreement (Table 8 and Fig. 11). For all three glaciers and periods studied the differences are within the error margins.

6 Discussion

6.1 More accurate modelling through integrating snowline observations

In order to demonstrate the advantage of ~~integrating~~ using snowline observations on repeated remote sensing data throughout the melting season for increasing the confidence in mass balance modelling, we ran the same accumulation and temperature-index model without the use of ~~snowline~~ snowlines or any other direct observations for calibration for all three glaciers from 2004 to 2016 (See Section 3.6). The same constant parameters were used (Table 3). We chose C_{prec} to account for a 20%-

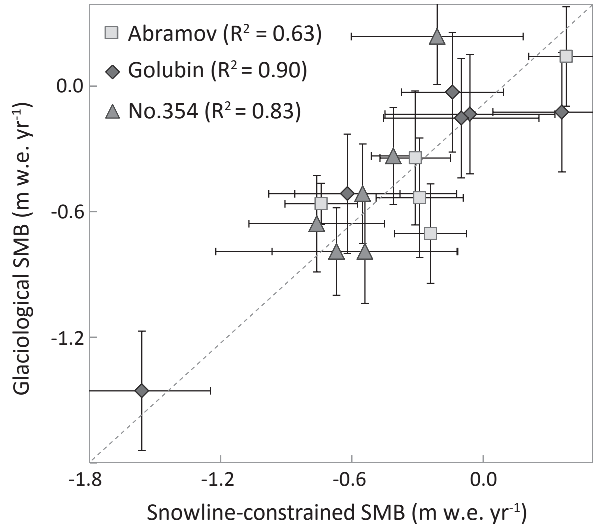

Figure 9. Comparison of ~~snowline-derived mass balances~~ ?modelled annual SMB constrained by snowline observations and glaciological ~~mass balances~~ ?SMB for Abramov (squares), Golubin (diamonds), and Glacier No. 354 (triangles). Uncertainties in the annual ~~mass balances~~ ?SMB are indicated.

Table 7. Annual ~~surface mass balance $B_{\mathrm{a(meas)}}$~~ ?SMB $B_{\mathrm{sfc(meas)}}$ for the measurement periods (i.e., exact dates of the surveys ?(Table 2)?) based on direct glaciological ~~surveys~~ ?measurements and on the ~~snowline approach~~ ?snowline-constrained model for the three glaciers in m w.e ~~a~~?yr^{-1}.

	Abramov		Golubin		?G
year	glaciological	~~snowline-derived~~ ?snowline-constrained	glaciological	~~snowline-derived~~ ?snowline-constrained	g
2011			-0.06 ± 0.30	-0.05 ± 0.39	−
2012	-0.29 ± 0.30	-0.47 ± 0.20	-0.14 ± 0.30	$+0.06 \pm 0.23$	−
2013	-0.31 ± 0.34	-0.27 ± 0.16	-0.10 ± 0.30	-0.07 ± 0.36	−
2014	-0.74 ± 0.10	-0.50 ± 0.17	-1.56 ± 0.30	-1.44 ± 0.31	−
2015	-0.24 ± 0.25	-0.65 ± 0.16	-0.62 ± 0.30	-0.45 ± 0.24	−
2016	$+0.38 \pm 0.25$	$+0.24 \pm 0.17$	$+0.36 \pm 0.30$	-0.04 ± 0.31	−
~~2011–2016~~ ?2011-2016	-0.24 ± 0.25	-0.33 ± 0.17	-0.35 ± 0.30	-0.33 ± 0.31	−

measurement error of ~~the recorded~~ observed precipitation (Sevruk, 1981), and a combination for DDF_{ice} (7.0 mm day^{-1} °C^{-1}) and DDF_{snow} (5.5 mm day^{-1} °C^{-1}) as recommended by Hock (2003) for the former Soviet territory, for all three glaciers. ~~The~~ Similar values were used to model glaciers in the Tien Shan and Himalayas (e.g. Zhang et al., 2006; Wu et al., 2011; Shea et al., 2015) . All parameters were held constant over time. Figure 12 shows the difference between the cumulative ~~mass balance~~ SMB derived from our model constrained by snowline observations, and the results obtained with an unconstrained mass balance

Table 8. Geodetic mass ~~balance~~ ?change $\Delta M_{\mathrm{geod(meas)}}$ and the total annual mass change derived from the snowline approach ~~$\Delta M_{\mathrm{snl(meas)}}$~~ ?$\Delta M_{\mathrm{tsl(meas)}}$ for the three glaciers and for the periods corresponding to the geodetic ~~survey~~ ?surveys in m w.e?. ~~a~~?yr^{-1}.

	$\Delta M_{\mathrm{geod(meas)}}$	~~$\Delta M_{\mathrm{snl(meas)}}$~~ ?$\Delta M_{\mathrm{tsl(meas)}}$
Abramov		
~~2003–2015~~ ?2003-2015	−0.39±0.16	−0.25±0.20
~~2011–2015~~ ?2011-2015	−0.36±0.26	−0.43±0.17
Golubin		
2006–2014	−~~0.22~~?0.30±~~0.42~~?0.37	−0.38± 0.35
?Glacier No. 354		
~~2003–2012~~ ?2003-2012	−0.42 ±0.07	−0.25 ±0.31
~~2012–2015~~ ?2012-2015	−0.58 ±0.31	−0.53 ±0.43

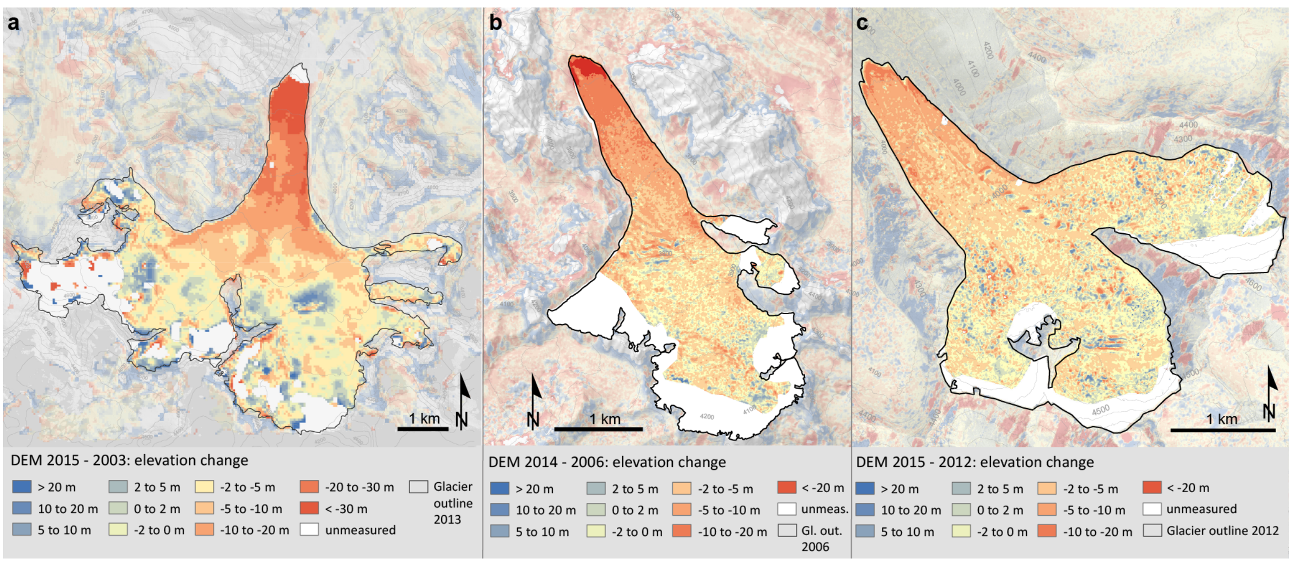

Figure 10. Geodetic mass balance for (~~a~~**?a**) Abramov ~~Glacier~~ from 2003 to 2015, (~~b~~**?b**) Golubin ~~Glacier~~ from 2006 to 2014 and for (~~c~~**?c**) Glacier No. 354 from 2012 to 2015.

model. The results clearly indicate the potential of the snowline approach to infer ~~mass balance~~ SMB series of unmeasured glaciers without any additional information. The unconstrained mass balance model overestimates mass loss by ~~roughly ten~~ almost five times for Abramov and ~~about five times for Golubin~~for Glacier No. 354, whereas mass loss for ~~Glacier No. 354 is strongly underestimated~~ Golubin is about three times higher (Fig. 12).

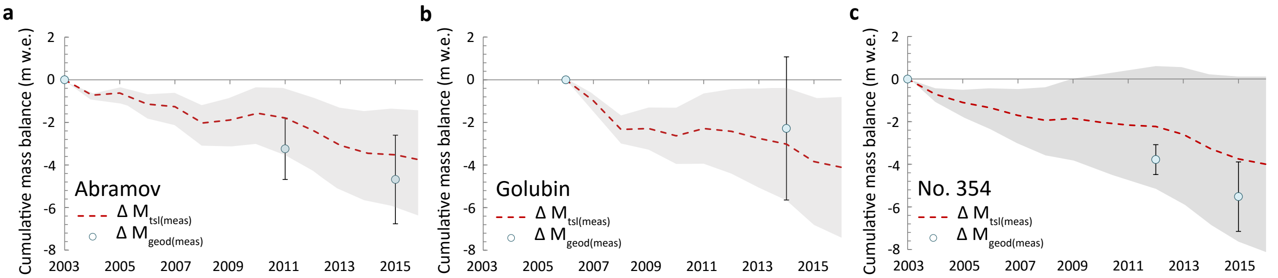

Figure 11. ~~Snowline-derived annual surface~~ ?Cumulative snowline-constrained modelled mass ~~balance~~ ?change $\Delta M_{\mathrm{tsl(meas)}}$ (red) in comparison to the geodetic mass change $\Delta M_{\mathrm{geod(meas)}}$ (circles) for ~~all three glaciers for~~ ?(?**a**?) Abramov, (?**b**?) Golubin and (?**c**?) Glacier No. 354. The shading indicates the ~~hydrological year~~?uncertainty range of the mass change from the snowline approach.

~~Cumulative snowline-derived mass change (red) in comparison to the geodetic mass change (circles) for (a) Abramov, (b) Golubin and (c) Glacier No. 354. The shading indicates the uncertainty range of the snowline-derived mass change.~~

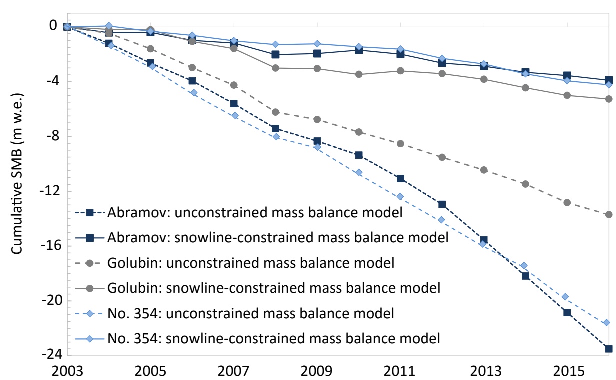

Figure 12. Comparison of the cumulative ~~mass balance~~ ?SMB derived from unconstrained mass balance modelling to ~~snowline-derived mass balance series~~ ?the results obtained from ?snowline-constrained modelling from 2004 to 2016.

6.2 Intercomparison of methods to determine glacier mass balance

A satisfying agreement was found between all three independent methods used to compute glacier-wide mass balance for the three benchmark glaciers in the Central Tien Shan and Pamir-Alay for the past two decades. In the following, we discuss shortcomings and advantages of each method and point out the limitations of the individual approaches.

The snowline model ~~represents~~ reproduces the direct measurements well and ~~performs satisfactory~~ shows a satisfactory performance for all three glaciers (Table 8, 6 and Fig. 13). For Glacier No. 354, a larger misfit between the glaciological ~~balance and the snowline model~~ SMB and the snowline-constrained model results was found, especially for 2011. A possible reason might be the limited stake network at the initiation of the monitoring programme, ~~large~~ errors of the stake readings and an unknown measurement date for some ablation stakes, affecting the calculation of the glaciological ~~mass balance~~ SMB for the considered year. Discrepancies between the two approaches are also found ~~at~~ for Golubin for 2016 and ~~at~~ for Abramov for 2015. For Abramov, summer snowfalls in mid-August 2015 stopped the ablation season early. This pattern is mirrored in the daily ~~mass balance~~ SMB derived from the snowline approach. For Golubin, the last snowline observation is from the end of August and matches the field observations. No clear indication of a poor performance of the snowline approach could thus be identified for both ~~of the~~ glaciers for the considered years.

An important problem is related to the varying measurement periods of the glaciological ~~mass balances~~ SMBs for the selected glaciers (Table 2). Due to changing period lengths, the data do not always represent a complete mass-balance year, and might thus not be representative, making comparison of the results with other methods, glaciers and regions difficult. Interpretation of the results, their contextualization and application in other study fields, such as in hydrology or climatology, are also hampered through the varying and irregular investigation periods. Based on our methodology, we are now able to derive homogenous ~~glacier mass balances~~ SMBs for comparable periods of the hydrological year.

An important factor limiting the applicability of mass balance modelling constrained by snowline observations is the dependence on good satellite imagery to map the snowline throughout the ablation season. However, the sensitivity analysis (Section 4) shows that a minimum of only two images that are well distributed throughout the ablation season are sufficient to retrieve reliable results. Image availability is most important close to the end of the ablation season. Taking into account the increasing number of satellite sensors that provide a range of possibilities to observe snowlines in the future will partly resolve this limitation. By comparing the snowline-derived daily ~~mass balance~~ SMBs for the years in which seasonal in situ measurements are available, we were able to investigate the effect on the results of the two parameters used for model calibration. Figure 13b shows that the mass balance of Golubin is slightly underestimated at the beginning of the ablation season, and hence the modelled melt is also too low. This shortcoming of the calibration procedure cannot be overcome without including additional data~~.~~, such as e.g. measurements of winter snow accumulation which is difficult on remote glaciers.

SMBs inferred from the snowline approach are closely tied to the representativeness of snowline observations. The method might be able to yield reliable SMB estimates for many glaciers in different climatic regimes, for which the transient snowline is an indicator of the surface mass balance. The relationship between the snowline and the SMB can however be importantly challenged when the position of the transient snowline is blurred by fresh snow or superimposed ice. The applicability of the snowline approach presented here can thus be critical when the transient snowline on remote sensing data cannot unambiguously be identified. This is mainly a problem for glaciers with a summer accumulation regime due to frequent fresh snow falls, and glaciers with a high relevance of superimposed ice.

The geodetic mass balance and the ~~snowline-derived results~~ results obtained from the snowline approach agree well, in particular for the recent years (Fig. 11). Overall, a slightly greater mass loss is calculated for Abramov and Glacier No. 354 using DEM differencing. Especially during the earlier part of our study period, the mass balance inferred with the snowline approach seems to be ~~too positive~~not negative enough. Limitations related to the geodetic approach are mainly connected to the limited stereo acquisitions in the first years of the ~~21st~~ 21st century. In recent years, image availability strongly increased, but it is still not common to find a suitable scene from the end of the hydrological year for ~~a selected~~ any glacier or region with

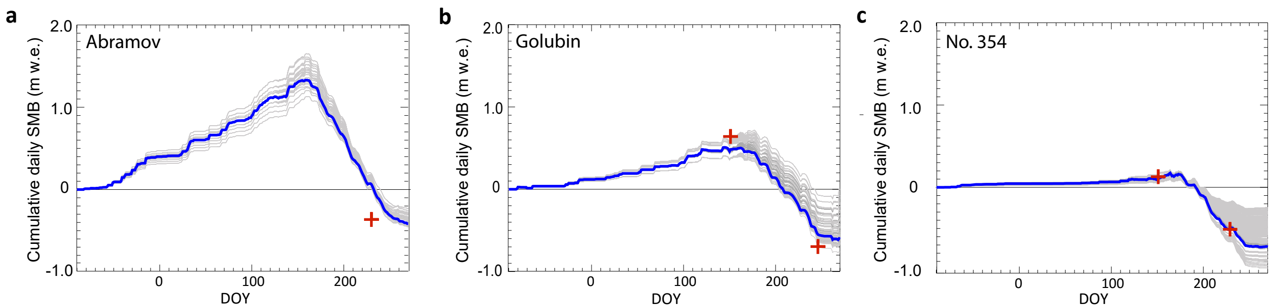

Figure 13. Cumulative daily glacier-wide ~~mass balance~~ ?SMBs inferred from the snowline approach for (~~a~~**?a**) Abramov, (~~b~~**?b**) Golubin and (~~c~~**?c**) ?Glacier No. 354 for the year 2014 (blue line). The grey lines indicate the spread obtained by using different constant parameters to run the model (Section 4) and the red cross indicates the measured glaciological ~~balance both~~ ?SMB for ?both the winter and the annual period.

sufficient quality for a sound geodetic evaluation. Fresh ~~snowfall~~ snow or low image contrast (in particular in the accumulation areas) interfere with ~~the~~ DEM quality but cannot be avoided and have thus to be corrected for, increasing the uncertainty of the result. We present geodetic mass balances for periods shorter than five years, a critical time interval for an accurate volume-to-mass conversion. Huss (2013) ~~shows~~ showed a high variability of the volume-to-mass conversion factor for short observation periods (≤ 3 years), especially for glaciers with close-to-zero mass balances in combination with strongly varying mass balance gradients. For the observation periods considered in this study, annual mass balances were predominantly negative but moderate variations of the mass balance gradients have been observed (Barandun et al., 2015; Kronenberg et al., 2016). We identified a rather large elevation change for the short observation periods, and are thus confident that the chosen conversion factor lies within the uncertainty range assigned here (see Section 4).

The glaciological and the ~~snowline-derived mass balances~~ modelled results constrained by snowline observations refer to surface mass balance components only. The geodetic mass balance, on the other hand, takes into account the total glacier mass change, thus including internal and basal ablation and accumulation. This is a limiting factor for direct comparison. Evidence of refreezing meltwater in cold firn is reported for all three glaciers (Suslov et al., 1980; Aizen et al., 1997; Dyurgerov and Mikhalenko, 1995) and can have a significant effect on the total mass change. The values used in this study to account for internal and basal mass balance are first-order approximations which improve the comparability between the different methods. However, the uncertainties in these estimates are considerable.

6.3 Comparison to other studies

We performed a comprehensive comparison of long-term averages of mass balance derived from the snowline approach to independent studies based on geodetic surveys using different sensors and modelling, both for the investigated glaciers ~~and for regional mass balances~~ as well as for the regional mass budget (Fig. 14). Note that the study periods vary between the different studies and results might thus not be directly comparable.

For Abramov~~Glacier~~, we find mass balances in between the results derived by Gardelle et al. (2013) and Brun et al. (2017) based on the comparison of DEMs, overlapping within the respective uncertainty ranges. Mass changes reported by Gardelle et al. (2013) are most likely too positive as SRTM C-Band penetration depth into snow (Kääb et al., 2015; Berthier et al., 2016) might have been underestimated for the cold and dry snow of accumulation areas (Dehecq et al., 2016). The average mass balance for Abramov of -0.38 ± 0.10 m w.e. ~~a~~yr^{-1} (2002-2014) derived by Brun et al. (2017) using multi-temporal ASTER DEMs indicates a stronger mass loss than ~~our study~~the results obtained with the snowline approach. We note, however, that the start and end dates of their geodetic mass balance ~~represents~~ assessment represent a mean over a mosaic of different dates, thus hampering ~~the direct comparisonto our results; in addition~~direct comparison. In addition, the differences are still within their error bounds. The results by Brun et al. (2017) are in line with the geodetic mass balance calculated in the present study for the period 2003 to 2015 based on high-resolution satellite images.

For Golubin~~Glacier~~, the inferred mass balance is in close agreement with the geodetic mass change reported by Bolch (2015) (Fig. 14b). Brun et al. (2017) computed a mass balance of -0.04 ± 0.19 m w.e. ~~a~~yr^{-1} for ≈2002-2013, which is consistently less negative than our estimate but still lies within the respective error bounds. For Glacier No. 354, an excellent agreement between all available mass balance assessments was found (Fig. 14c). Brun et al. (2017) reported a mass balance of -0.46 ± 0.19 m w.e. ~~a~~yr^{-1} for ≈2002-2014.

~~Furthermore, we~~ We also compared our results for the investigated glaciers to region-wide assessments in order to investigate their regional representativeness (Fig. 14d-f). Brun et al. (2017) divided the Pamir-Alay and the Pamir into two different regions, whereas Gardner et al. (2013), Gardelle et al. (2013), Kääb et al. (2015) and Farinotti et al. (2015) did not make this distinction. For the Pamir, widely varying mass balance estimates were presented by the different studies, which might be related to ~~the~~ important methodological differences and inconsistent time periods considered. Our results for Abramov are close to the average of the regional studies (Fig. 14d). The interannual variability and~~in particular~~ , in particular, a very negative mass balance ~~for~~ in 2008 and a positive balance in 2010 for Abramov found in the present study agrees well with modelled mass balance series reported by Pohl et al. (2017) for the Pamir from 2002 to 2013. The ~~snowline-derived~~ snowline-constrained modelled mass balance for Golubin agrees with the region-wide estimates by Brun et al. (2017) but indicates smaller mass losses than other large-scale studies (Fig. 14e). Close agreement between the different regional studies is found for the Central/Inner Tien Shan, where Glacier No. 354 is located (Fig. 14f).

7 Conclusions

In this study we used three independent methods to reconstruct robust mass balance series at high temporal resolution for Abramov, Golubin and Glacier No. 354 located in the Pamir-Alay and Tien Shan mountains for the past two decades – a period for which only little is known about glacier behaviour. We proposed a methodology to derive glacier ~~surface mass balances~~ SMB series for unmeasured glaciers based on mass balance modelling constrained by repeated snowline observations. We recommended including snowline observations in the glacier monitoring strategy to reduce uncertainty and to increase robustness of the data. We used extensive geodetic and glaciological surveys to validate the results ~~,~~ and found satisfying

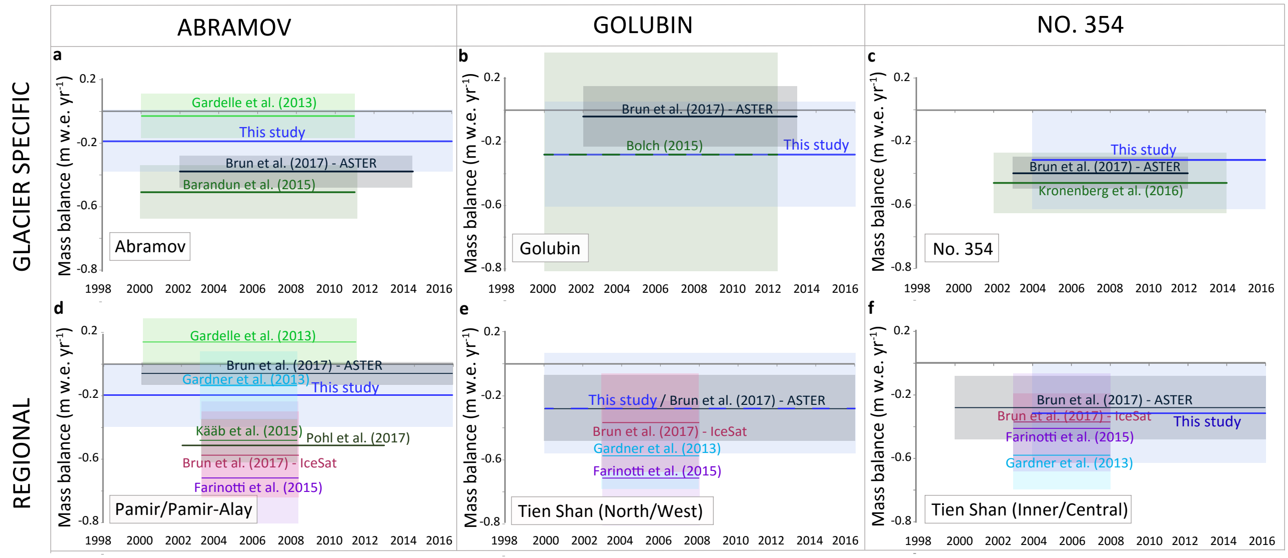

Figure 14. Long-term average mass balances from various studies in comparison with the ~~snowline-derived~~ ?snowline-constrained modelled mass balance for (~~a~~?**a**) Abramov, (~~b~~?**b**) Golubin, (~~c~~?**c**) ~~Gl.~~ ?Glacier No. 354. Results from the snowline approach for the three glaciers are compared to region-wide mass balance estimates for (~~d~~?**d**) the Pamir, for (~~e~~?**e**) Tien Shan (North/West) and for (~~f~~?**f**) the Tien Shan (Inner/Central). Lines indicate the mean annual mass balance over the respective periods for each study, and shaded squares represent the corresponding uncertainty. For the study by Brun et al. (2017) results based on ASTER DEMs and IceSat are presented separately.

agreement between the independent methods. Our snowline approach reproduced observed annual to decadal ~~mass balances satisfactorily~~ SMB for all three glaciers ~~,~~ and enabled the calculation of daily ~~mass balances~~ SMBs for arbitrary periods, and is, hence, capable of covering the entire hydrological year based on minimal data input. Some of the shortcomings of the glaciological and geodetic surveys could thus be overcome.

The results of all three methods confirm a continuous mass loss of the three ~~benchmark~~ glaciers Abramov, Golubin and Glacier No. 354 for the past two decades but no clear ~~mass balance~~ SMB trend could be identified for the time period considered. Our results suggest a slightly less negative ~~surface mass balance~~ SMBs for Abramov of -0.30 ± 0.19 m w.e. ~~a~~yr^{-1} located in the Pamir-Alay than for the Tien Shan glaciers Golubin of -0.41 ± 0.33 m w.e. ~~a~~yr^{-1} and Glacier No. 354 of -0.36 ± 0.32 m w.e. ~~a~~yr^{-1} from 2004 to 2016. Periods of almost balanced mass budgets were observed from 2002 to ~~2004~~ 2005 and from 2009 to 2011. The mass balance of 2006 to 2008 was very negative for Abramov and Golubin. Glacier No. 354 ~~shows a weaker inter-annual~~ showed a weaker interannual variability than the other two glaciers~~, explained by its more continental climate regime~~. Model sensitivity experiments revealed a relatively small sensitivity to the input parameters and the meteorological data used, indicating a considerable advantage in comparison to conventional mass balance modelling that does not include direct glacier-specific observations. Our results show that with a minimum of two snowline observations, ideally at the beginning and the end of the ablation season, reliable estimates of the annual ~~mass balance~~ SMB can be inferred.

At present, mass balance observations in the Pamir and Tien Shan ~~mountains~~ are sparse but crucially needed to improve understanding of glacier behaviour in the region and its effect on future water availability. Direct measurements are, however, costly and laborious and require an immense logistic effort. For remote and ~~inaccessible~~ unmonitored regions and countries, lacking in financial resources and infrastructure to support such monitoring programmes, our proposed approach delivers a tool for investigating and reconstructing the ~~mass balance of inaccessible~~ SMBs of unmeasured and remote glaciers with minimal effort. The integration of snowline observations into conventional modelling is shown to be highly beneficial ~~,~~ for filling the gaps in long-term ~~mass balance~~ SMB series for periods for which direct glaciological measurements were discontinued or are missing completely.

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