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Interactive comment on "Multi-decadal mass balance series of three Kyrgyz glaciers inferred from transient snowline observations" *by* Martina Barandun et al.

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Below we respond to all comments by Prof. Dr. M. Pelto (Reviewer 2). We mainly tried to clarify and complete imprecise sections, to remove inconsistencies and added suggested references in the revised manuscript.

The responses (normal font style) to the reviewers' comments (displayed in italic font style) are written directly into the reviews . The corresponding revised sentences in the manuscript are given in quotation marks.

We thank the referee for the valuable, constructive and detailed reflections and comments. The comments certainly improve the manuscript.

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) to Pelto 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.
"Evidence of persistent superimposed ice is found and Kronenberg and others (2016) estimated internal accumulation to be $+0.04$ 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.
"For Golubin and Glacier No. 354 a slightly more negative annual average balance of -0.41 ± 0.33 m w.e. yr^{-1} and -0.36 ± 0.32 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 and others, 2017). A predominant 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) and 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.
"Contrast becomes rather weak, especially when the snowline rises above the firn line (Rabatel and others, 2013, Want and others, 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.
"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 onwards."

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.
"A model-based spatial extrapolation of point measurements to the entire glacier surface after Huss and

others, (2009) was used to retrieve glacier-wide SMB for all years with direct measurements. The model is a combined distributed accumulation (Huss and others, 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.

"The vertical offset was reduced to 1.0 m (2003-2015) and to 0.6 m (2011-2015) for Abramov, to 0.7 m for Glacier No. 354 and to 1.8 m for Golubin."

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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 and others (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 mm day^{-1} °C^{-1} and not 5.49 mm day^{-1} °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.

"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."

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.

"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 the uncertainty for the respective periods."

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.

"We chose C_{prec} to account for a 20%-measurement error of the recorded 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., Zhang and others, 2006, Wu and others, 2011, Shea and others, 2015)."

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 and others, 2015, Kronenberg and others, 2016, Kenzhebaev and others, 2017). 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 (1986 or 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 and others (2015) from where we adopted the estimate of internal accumulation, the study by Bazhev (1973, IASH Publ. 95). was used for calibrating the refreezing model. In Barandun and others (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 and others, 1991, Journal Geophysical Research, 96). 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 and others, 1993). The results were finally compared to findings for Abramov presented by Bazhev (1973, IASH Publ. 95).

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.

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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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