Response letter

Subseasonal snowline dynamics of glaciers in Central Asia

Dilara Kim†, Enrico Mattea, Mattia Callegari, Tomas Saks, Rulsan Kenzhebayev, Erlan Azisov, Tobias Ullmann, Sebastian Buchelt, Martin Hoelzle, Martina Barandun

Dear Editor,

First of all, we would like to thank the reviewers for their time and their constructive feedback. Second, we regret to inform you that, sadly, the lead author of the work discussed here, Dilara Kim, passed away before this revision could be completed. Nevertheless, the other authors take full responsibility for handling the feedback and will prepare a revised manuscript in which the reviewers' comments are addressed in the best possible manner. We are currently working on recovering the complete code and data, which will then be made available on Zenodo and GEE. We will seek professional help to rebuild the missing code parts and integrate the needed changes for the revised manuscript, ensuring full reproducibility of the methods. We hope to meet all the proposed deadlines; however, some extra time might be needed for the full revision.

The main supervisor of D. Kim, M. Barandun, takes over the corresponded authorship; in addition, she manages the review process the co-author team is currently performing. We truly appreciate your understanding for the delay, and we hope that our answers are satisfying.

We thank you for your understanding.
Kind regards,

Martina Barandun, in the name of the co-author team.

- Both reviewers have questioned the benefits of using Sentinel-1 for mapping snow covered area fractions (SCAFs) as proposed here. They have highlighted strong limitations of the method. We understand their concerns. However, the primary motivation for including Sentinel-1 (S-1) was its use as a complementary data source, which was expected to increase the number of observations available for deriving higher spatial resolution SCAF time series from MODIS. Based on our results, the added value of S-1 might be limited in this case, as criticized by the reviewers. However, our results also show that S-1 and Sentinel-2 (S-2), despite their completely different data types and approaches, can be successfully combined to generate SCAF estimates of comparable quality. This is an important result for potential transfer of this method to areas with more frequent cloud cover. We will explain this more clearly in the manuscript.

- We have significantly restructured and reworked the manuscript with a focus on the clarification of the Introduction, Methods, and Discussion sections. We believe that we can answer to all of the reviewers concerns regarding the methodology by 1) clarifying the text, 2) restructuring the Uncertainties and limitations section, 3) adding examples of the classification in the Annex, and 4) adding a sensitivity analysis on (i) the rigid outlines used here and (ii) the thresholding for the Otsu threshold.

Below, we provide itemized answers to all the comments, and we describe how these are now incorporated into the revised manuscript. Our responses (normal font style) are added directly after each comment (italic font style). The corresponding revised text in the manuscript is presented as footnotes for each comment, stating the section in which the fragments can be found.

1 Reviewer #1

1.1 General Comments

I thoroughly enjoyed reading this paper. The paper proposes a robust and important new method. It successfully bridges a critical data gap by generating a 24-year, close-to-daily time series of the Snow-Covered Area Fraction (SCAF) for four reference glaciers in the Pamir and Tien Shan. The integration of MODIS, Sentinel-1, and Sentinel-2 data to derive SCAF is technically sound and innovative, offering a powerful tool for improving seasonal runoff forecasts and understanding glacier-climate interactions in water-scarce Central Asia. The manuscript presents significant new data and a novel methodology that addresses a major observational deficit in glaciology. The core finding—that similar annual mass balance values can result from vastly different sub-seasonal melt dynamics—is highly relevant to water resource management. However, several methodological details, particularly regarding the data combination (SCAF S1 and SCAF S2) and validation metrics, require clarification and stronger justification to ensure the robustness and reproducibility of the proposed SCAF.

We thank the reviewer for the positive feedback about the manuscript, highlighting the importance of the developed method to better understand glacier-climate interaction in the region.

The main challenge in reading the paper is understanding the use of a static RGI outline for the calculation of not only the snow-covered area fraction, but also the mean near infrared values from MODIS. Seeing as there are only four glaciers in the study and 24 years of study, I think it is reasonable to ask the authors to use time-dynamic glacier outlines. This would correct two major limitations: 1) The mean near-infrared (NIR) values are currently biased with off-glacier values (water, rock, etc.) and this bias increases over time as the glacier retreats and the RGI polygon stays the same; and 2) the SCAF is always using the static RGI polygon area as the total glacier area, even though the glacier is changing over time. This comment appears a few times in the General section as well.

Thank you for your comment.

As our aim is to develop a method applicable at a regional level, we prefer to rely on regional datasets such as RGI. We agree that, in principle, the use of time-dependent glacier outlines would provide a more accurate representation of glacier extent and would eliminate any potential bias associated with glacier retreat. However, as the study covers a period of 20 years, the error introduced by the overestimated outlines is negligible. To show this, we have added a sensitivity analysis in the Appendixes and extended the Discussion section based on the results of said sensitivity analysis.

To assess whether the use of a static glacier outline introduces a significant bias in our analysis, we quantified the maximum possible error in both the MODIS mean near-infrared (NIR) reflectance and the S-2 SCAF. To do so, we used Abramov glacier as a representative example because glacier outlines are available from 2000 to 2023. Fig. 1 shows the outlines overlaid on a sample MODIS NIR image to illustrate the relationship between glacier retreat and the 250 m MODIS pixel size.

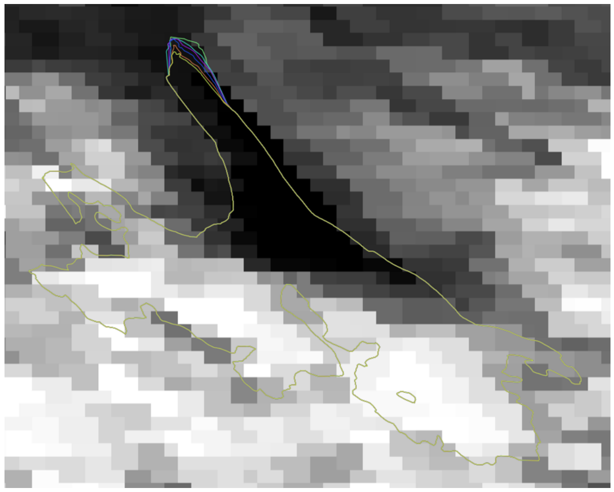

Figure 1: [corresponds to Figure F1 in the revised manuscript] Abramov glacier outlines for years 2000, 2005, 2010, 2015, 2020, and 2023 overlaid to a sample MODIS NIR image

The corresponding number of MOD09 pixels contained within the glacier outline is showed in Table 1. Thus, over a 24-year period, the glacier outline changes by only 6 MODIS pixels (approximately 1.7% of the total glacier area).

Table 1: [corresponds to Table F1 in the revised manuscript] Number of pixels in the glacier outline

YEAR	MOD09 pixels
2000	353
2005	351
2010	351
2015	350
2020	347
2023	347

To estimate the maximum possible bias that can be introduced by using a static glacier outline, we consider the worst-case scenario, i.e., the 2000 outline (353 pixels) is used to compute the mean NIR reflectance in 2023, when the correct outline contains 347 pixels.

The mean NIR reflectance of 2023 computed with the static outline corresponding to year 2000 is

$$\tilde{\mu} = \frac{1}{N} \sum_{i=1}^{N} x_i$$

where $N = 353$ is the number of pixels in the static outline, and x_i is the NIR reflectance of pixel i.

The correct mean, computed using the updated glacier outline, is

$$\mu = \frac{1}{M}\sum_{i=1}^{M} x_i$$

where $M = 347$ is the number of pixels in the 2023 outline. We can rewrite the static mean as

$$\tilde{\mu} = \frac{1}{N}\left(\sum_{i=1}^{M} x_i + \sum_{i=M+1}^{N} x_i\right) = \frac{1}{N}\left(M\mu + \sum_{i=M+1}^{N} x_i\right).$$

The maximum possible error occurs under the conservative assumption of the glacier having the maximum possible mean reflectance ($\mu = 1$) and all pixels being included only because of the outdated outline has zero reflectance:

$$x_i = 0, \qquad i = M+1, \ldots, N.$$

Under these assumption,

$$\tilde{\mu} = \frac{1}{353}(347 + 0) = 0.983,$$

corresponding to a maximum error of

$$1 - 0.983 = 0.017.$$

Therefore, even in this extreme worst-case scenario, the maximum possible bias in the mean NIR reflectance is less than 0.02. In practice, the error is expected to be substantially smaller because the excluded pixels are unlikely to have 0 reflectance and the glacier-wide mean reflectance is generally lower than 1.

The same analysis was performed for the SCAF calculation. Since SCAF is derived from S-2 imagery, the corresponding number of S-2 pixels within the glacier outline is presented in Table 2.

Table 2: [corresponds to Table F2 in the revised manuscript] Number of Sentinel-2 pixels within the glacier outline

Year	Sentinel-2 pixels
2000	215488
2005	215299
2010	214792
2015	213999
2020	212944
2023	212394

Similarly to the computation of the mean NIR reflectance, the 2023 SCAF computed using the static outline corresponding to the year 2000 is

$$\widetilde{\mathrm{SCAF}} = \frac{1}{N}\sum_{i=1}^{N} x_i,$$

where $N = 215488$ is the number of pixels in the static outline, and x_i is a binary variable equal to 1 for snow-covered pixels and 0 otherwise.

Using the same formulation as for the mean NIR reflectance, the maximum possible error occurs when the glacier is completely snow covered (SCAF = 1), while all additional pixels included by the static outline are snow free. The resulting maximum error is

$$1 - \frac{212394}{215488} = 0.014 = 1.4\%.$$

In summary, the use of static glacier outlines introduces a maximum theoretical error of less than 2% for the MODIS mean NIR reflectance and 1.4% for the S-2 SCAF calculation. Both values represent conservative upper bounds, and the actual errors are expected to be considerably smaller. Figure 2 shows the actual difference in SCAF when using GLIMS/RGI outlines or the outlines from a specific year (e.g., 2013). We therefore conclude that the use of static RGI outlines does not meaningfully affect the results of this study.

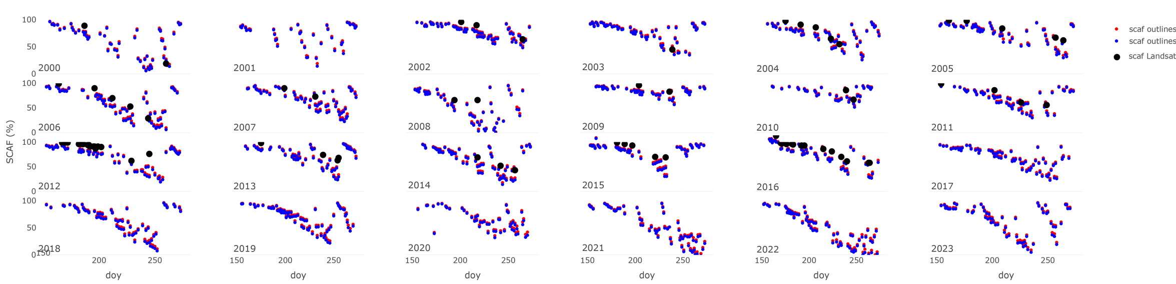

Figure 2: [corresponds to Figure F2 in the revised manuscript] Comparison of the SCAF time series for Abramov using GLIMS outlines (red) or outlines from 2013 (blue), validated with manually observed SCAFs from Landsat (black).

Discussion: We use fixed glacier outline from GLIMS and RGI v6 for the entire study period. As glaciers retreat, the fraction of snow within fixed glacier area reduces over time, exposing bed rock or sediments at the surface. Additionally, the geometry of the glacier and the orientation of its tongue can change over time (Khromova et al., 2014). When assessing whether the use of a static glacier outline may introduce significant bias, a maximum theoretical error of less than 2% for the MODIS mean NIR reflectance and 1.4% for the S-2 SCAF calculation was obtained (see Appendix D). Both values are conservative upper bounds, and the actual errors are expected to be considerably smaller; an example is shown in Figure F2. We therefore conclude that the use of static RGI outlines does not significantly affect the results of this study.

There are no examples of what the results from the Otsu classification, S1 classification, or resulting MODIS SCAF actually look like. It would be very helpful for the reader to see what these "500m" modis pixels look like overlain on the glacier. What the ice vs snow classification looks like from Otsu on S2, and what the results from S1 look like as well. I strongly suggest a supplementary or main text figure that demonstrates what these data look like.

The strength of this method lies in the fact that it does not rely solely on low-resolution MODIS data for SCAF mapping but rather relates it to higher-resolution imagery. This allows us to take advantage of the MODIS sensor's higher temporal resolution and the Sentinel sensors' higher spatial resolution. Therefore, we are not so much interested in the accuracy with which the SCAF is represented directly by MODIS or its mean NIR as we are in the existence of a relationship between the snow depletion mapped in detail using Sentinel data and the mean NIR value over the glacier area. The $glacierSCAF_{MODIS}$ is thus not based on the mean NIR value but on a SCAF derived from higher-resolution data representing a condition reflecting a specific mean NIR MODIS value observed on close-to-daily resolution. Furthermore, the $glacierSCAF_{MODIS}$ is not a spatially distributed product but rather a SCAF value based on the relationship between the mean NIR MODIS value and the Sentinel derived SCAF, as shown in Fig. 3 of the manuscript. Examples of Otsu (Fig. 3) and S1 classifications (Fig. 4) are now available in the Annexes of the revised manuscript.

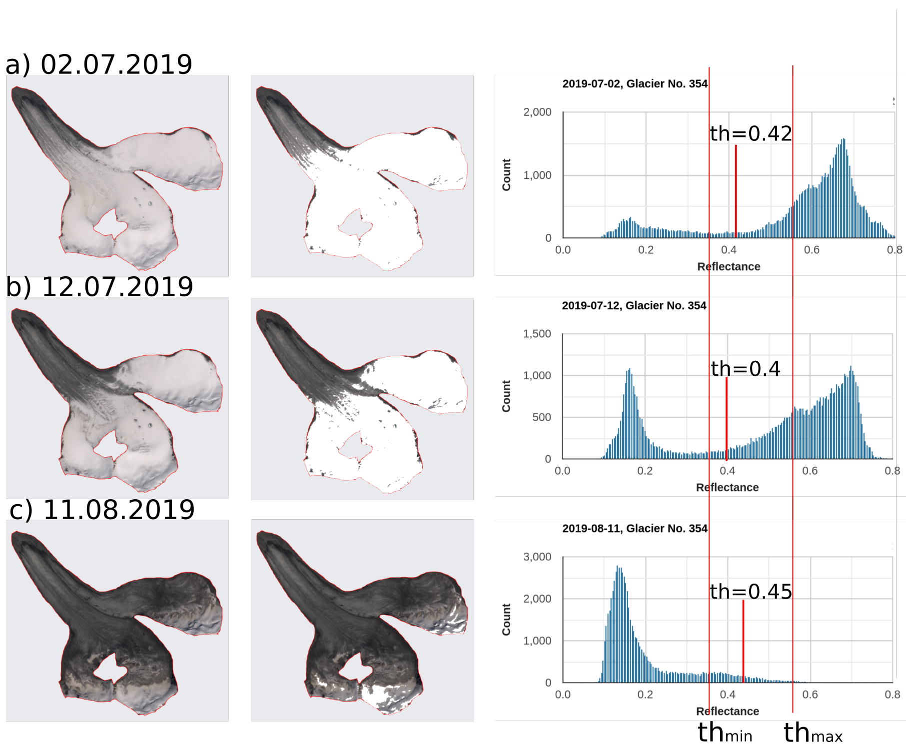

Figure 3: [corresponds to Figure B1 in the revised manuscript] Snowline mapping for Glacier No. 354 from Sentinel-2 with Otsu threshold algorithm for three consecutive acquisitions in 2019 (a-c). Left: Sentinel-2 topographically corrected images. Center: identified snow class in white color. Right: frequency histogram of NIR topographically corrected images and respective optimal (th), minimum (th_{min}), and maximum (th_{max}) thresholds.

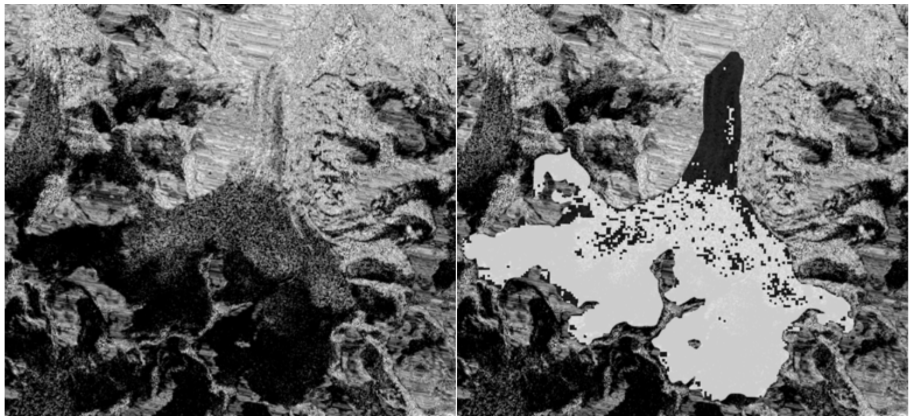

Figure 4: [corresponds to Figure F3 in the revised manuscript] (left) Sentinel-1 SAR backscatter image. (right) Corresponding snow classification result. Pixel classified as snow are displayed in light gray before the snowline altitude (SLA) correction.

It is a bit unclear to me what Sentinel-1 contributed in this paper and if it was required. A sensitivity analysis or improved explanation of what was gained from having S1 in the study would be helpful.

The primary motivation for including S-1 was its weather-independent acquisition capability, which was expected to increase the number of observations available for deriving higher resolution SCAF estimates, especially in regions with frequent summer cloud cover such as the Central Tien Shan. A denser set of higher resolution observations was expected to improve the relationship between the MODIS mean NIR signal and the corresponding SCAF values. Furthermore, the inclusion of S-1 would provide an important assessment of the capabilities and limitations of SAR data for deriving complementary high-resolution SCAF values in case of frequent cloud cover. We clarify this motivation more explicitly in the revised manuscript and further expand the discussion on the contribution of S-1 by explaining that, although the practical benefit proved to be smaller than initially anticipated due to the challenges of wet-snow mapping with C-band SAR and the overlap with available optical observations from MODIS, we still believe that retaining the S-1 component strengthens the methodological evaluation of the proposed approach, even though excluding it would likely have only a minor impact on the final MODIS-derived SCAF time series.

Discussion: Although S-1 images are not affected by clouds, dry snow is transparent in the C band (Nagler et al., 2016), which excludes accurate capture of summer snowfalls and the end-of-season snowline. Also, a fixed threshold of -6 dB for wet-snow detection is applied here, which is not necessarily optimal for all the study glaciers throughout the ablation season due to the differences in climatic settings, sensor viewing angle, and polarization (Winsvold et al., 2018; Buchelt et al., 2022). Besides, steep terrain could lead to radar layover and shadow effects; however, this issue is limited to very small parts at the study sites. Nevertheless, S-1 can provide valuable snowline observation information independently (see Fig. 4). The potential of S-1 is not fully revealed in the present work as this is only used as a backup in case of unavailable or cloud-obscured S-2 acquisitions. In addition, the limitation of S-1 to the main ablation period results in the necessity to always include cloud-free optical images. Thus, the benefit of S-1 is limited for the proposed application as long as enough reliable cloud-free S-2 acquisitions are available.

I'm surprised that links to climate are not stronger in the paper. The glacier model is interesting, but it does not get into trying to explain some of the interannual variability with simple metrics such as total winter accumulation, mean summer temperature, which have been shown to be strong predictors. Essentially, what I am getting at here is that the regions may not all behave the same, but is it simply that the climate is not the same, and they all do react similarly to similar perturbations (i.e. a big snow year with a cool summer = low snowline, or a light snow year with a hot summer = high snowline).

Thank you for your comment; we totally agree. Still, our analysis of a selected glacier has taught us that a straightforward analysis using meteorological drivers is difficult. While it is true that large perturbations affect snowlines similarly, we have also seen that a combination of different events occurring at different times before and during the melt season can significantly alter their position. We describe this effect in the Discussion section. This issue renders it very difficult to make clear and consistent statements about the drivers behind snowline changes during the summer. The examples mentioned by the reviewer are, of course, true; they are also among the most obvious. In reality, however, the scenario is much more complicated. Perhaps we should start by asking what constitutes a cold summer and when a summer is cold enough to prevent the snowline from rising, and so on. For example, high June temperatures may be more important than July temperatures and fresh snowfall in summer can significantly alter melt rates, even if the summer is generally warm. We agree with the reviewer that there is a lot of hidden information in the observed snowlines that could improve our understanding of glacier-climate interactions and how the region responds to changing atmospheric conditions. To improve this understanding is the ultimate aim of this work. For this manuscript, however, the objective is to develop and test the methodology, and to demonstrate that snowlines can be used to approximate subseasonal glacier's mass balance and can be linked to different climatic drivers. The next logical step is to apply the methodology discussed here at the regional level. Given that direct meteorological observations are sparse and therefore not enough to conduct an in-depth analysis on regional heterogeneity, climate influences, and responses of the entire region, the method proposed in the present work would provide enough data and at the right scale for comparison with gridded meteorological data.

1.2 Minor Comments

Title: Suggest to change to "Sub-seasonal snow cover dynamics on four glaciers in Central Asia from multi-sensor satellite observations". The current title sounds like a regional assessment of all glaciers.

The title is changed in the revised manuscript including also the reviewer #2 suggestion.

Title: Subseasonal snow cover changes on four glaciers in Central Asia from multisensor satellite observations, 2000-2023

L19: Is this the appropriate way to format the WMO reference? Usually we see use: (WMO, 2022)

We have carefully double checked all references and corrected any missing or formatting issues. We deeply apologize for the inaccuracies in the reference formatting throughout the manuscript.

L20: Consider replacing "drastic" for a more common and scientifically precise term (e.g. Significant, Profound, Far-reaching, Severe)

This is changed accordingly in the revised manuscript.

L25: Unclear on the years of the "Soviet times". Please be more specific (e.g. prior to 1985). and *L26: Specify the year of the dissolution of the Soviet State?*

The Introduction section is significantly restructured in the revised manuscript having taken into consideration the comments from both reviewer #1 and reviewer #2 . The section mentioned in the present comment is now shortened to:

Introduction: Almost all glacier monitoring programs in the former Central Asian Soviet Union collapsed in the early 1990s, following the dissolution of the Soviet Union in December 1991.

L33: Please explain the AAR concept.

The Introduction section is significantly shortened and restructured in the revised manuscript. The part mentioned in this comment is rephrased taking into consideration also the comments from reviewer #2 to better explain 1) existing concepts, 2) their shortcomings, and 3) what we propose in this study. We have decided to remove the paragraph on the AAR/ELA method since this is not relevant for our manuscript and rather deviates from the main aim and confuses the reader. We now highlight the concept of using directly the snowlines/SCAFs as a proxy for mass balance. This section reads now:

Introduction: In the absence of direct glacier observations, one of the most common methods to infer annual glacier mass change (Østrem, 1975; Braithwaite, 1984; Kuhn, 1990; Dyurgerov, 1996) or regional glacier mass balance (Kulkarni, 1992; Rabatel et al., 2017) is to use the linear relationship between the remotely observable end-of-summer snowline or snow-covered area fraction (SCAF) and the glacier mass balance. The snowline marks the transition between snow and bare ice surfaces and thus thus approximates the limit between the accumulation and ablation areas of the glacier. The SCAF is the area above the snowline in relation to the total glacier area and therefore represents an altitude-independent proxy for the mass balance (Huss et al., 2013). Dyurgerov (1996) observed the transient snowline as a proxy for the subseasonal mass balance, and Pelto (2011) calculated the seasonal snowline rate of change from the available Landsat observations for the Taku glacier, Alaska. The author tied the snowline migration rate to changes in mass balance gradient and concluded that there is a potential for an efficient mass balance assessment from high temporally resolved snowline time series for many years and on many glaciers. Huss et al. (2013) and Barandun et al. (2018) replaced the snowline with the SCAF and its rate of change to calibrate directly a glacier mass balance model.

L36: Elaborate on the linear relationship, is this for all glaciers? Also suggest replacing usually with commonly.

This section is now rephrased and restructured taking into consideration also the above comment to better explain 1) existing concepts, 2) their shortcomings, and 3) what we propose in this study. Please refer also to our responses to the comments above.

L37: replace "on with "in" ... remote sensing images

This is changed accordingly in the revised manuscript. Thank you.

L42: replace "and concluded on the potential" with "and concluded that there is a potential"

This is changed accordingly in the revised manuscript. Thank you.

L46: TSL not defined

We no longer use this abbreviation in the revised manuscript; instead, this is replaced with 'transient snowline'.

Explain the difference between the SCAF and the AAR

Please refer to the reply to the comment above. The explanation regarding SCAF is expanded in the revised manuscript, and the part regarding AAR is removed.

Introduction: The snowline marks the transition between the snow and bare ice surfaces and thus approximates the limit between the accumulation and ablation areas of the glacier. The SCAF is the area above the snowline in relation to the total glacier area and therefore represents an altitude-independent proxy for the mass balance (Huss et al., 2013).

L56: Suggest "Snow in the accumulation..."

This is changed accordingly in the revised manuscript. Thank you.

L66-68: Not sure this explanation does justice to the massive potential of ML workflows in recent papers assessing TSL etc. over large areas and for many glaciers, and for multiple classes, like snow, firn, ice, supraglacial ponds, off glacier areas, clouds, shadows, etc.

This statement is rephrased in the revised manuscript to better reflect the current state of the art and better highlight the benefits of machine learning (ML) workflows, especially for large scale surface mapping. Our intention was never to question their general potential, but rather to point out that supervised ML approaches typically require representative annotated training data and that their transferability across regions, sensors, and acquisition conditions needs to be carefully evaluated.

Introduction: More recent methods have applied machine learning (ML) to obtain the snowline (Prieur et al., 2022; Adam, 1997; Aberle et al., 2025). Supervised ML approaches generally require representative annotated training data, and their transferability across regions, sensors, and varying acquisition conditions should be carefully evaluated. Threshold-based methods, in contrast, do not require labeled training data but rely on predefined spectral assumptions and usually require calibration of threshold values when transferred to different regions, sensors, or environmental conditions, although this calibration is often more straightforward than generating new training datasets. Unsupervised methods, such as Otsu thresholding (Rastner et al., 2019), are generally more transferable because they determine thresholds directly from the image data. However, they perform well only when the target classes are clearly separable in feature space and may fail when the image is dominated by a single class (e.g., glaciers that are almost entirely snow covered) or when class distributions strongly overlap. More generally, both threshold-based and unsupervised approaches are sensitive to illumination, atmospheric conditions, and surface heterogeneity, and they often struggle to distinguish spectrally similar glacier surface classes.

L76: Space in front of Aberle"

This is changed accordingly in the revised manuscript. Thank you.

L91/L107/L110/116/296/371/428/514/559: Many instances of "??" in manuscript for refs and figure cross-references. Please correct.

We truly apologize for the many mistakes in the references. The manuscript has been revised thoroughly.

L98: Can you expand on the idea of "contrasting glacier mass balance responses (Fig. 1)". I'm looking at Figure 1 and not sure what is contrasting... Is it regional, aspect, elevation?

The contrasting responses of glaciers in the region have been widely documented (e.g., Barandun et al., 2021; Brun et al., 2017; Hugonnet et al., 2021). However, clear climatic and morphological drivers of this heterogeneous responses throughout the Tien Shan and Pamir have yet to be found, mainly due to a lack of observations (Barandun and Pohl, 2023; Brun et al., 2019). We include the relevant research and references in the revised manuscript and provide further explanations of the heterogeneity and the unknown drivers; however, we do not wish to go into too much detail here.

Introduction: The overall dry and cold mountain ranges Tien Shan and Pamir are characterized by heterogeneous glacier mass balance responses (Fig. 1) (Barandun et al., 2021; Barandun and Pohl, 2023; Hugonnet et al., 2021), with some glaciers close to the equilibrium (Barandun et al., 2021; Miles et al., 2021; Hugonnet et al., 2021). Glacier responses in Central Asia are heterogeneous due to complex topomorphological characteristics (Brun et al., 2019), varying atmospheric circulation patterns and climate sensitivity (Fujita, 2008), and surge activities (Mattea et al., 2026). However, clear climatic, topographic, and morphological drivers of the heterogeneity have yet to be found, mainly due to a lack of observations (Barandun and Pohl, 2023).

L100: Remove "." In front of "(Pohl et al.[...]"

This is changed accordingly in the revised manuscript. Thank you.

L102: add "e.g." to the "Glacier No. 354"

This is changed accordingly in the revised manuscript. Thank you.

Table 1: replace "in situ" with "in-situ" in caption, and add "°N and °E" to coordinates

This is changed accordingly in the revised manuscript. Thank you.

Figure 1: I don't think these are pie charts (like the caption suggests). There are colored bubbles/dots. I assume this is a regular grid of sorts. Can the grid resolution be specified in the caption (10x10km). Can the caption describe the SMB data a bit more in the caption (modelled, observed, years etc.)

We provide a better explanation of the figure in the caption and add additional information in the revised manuscript.

Figure 1: Overview map of the study region. The circles represent area-weighted mean mass balance modeled by (Barandun et al., 2021) between 2000-2018 (averaged within 0.25-degree grid cells using glacier centroids provided in the RGI). The four studied glaciers are marked in purple. The figure is adapted from Barandun et al. (2021).

Figure 1: Purple x and labels are hard to see. Perhaps change legend label lower limit from -1.87 to -1.9.

The readability of the figure is improved in the revised manuscript and its legend changed.

L116-117: Can the annual summer, winter, and annual mass balance of the 4 glaciers be shown somewhere? Perhaps in a supplement. Fig. 9B is great, but I would like to see the rest of the glaciers as well.

The same figures of the remaining three glaciers are now included in the Appendixes of the revised manuscript (Fig. 5, 6 and 7).

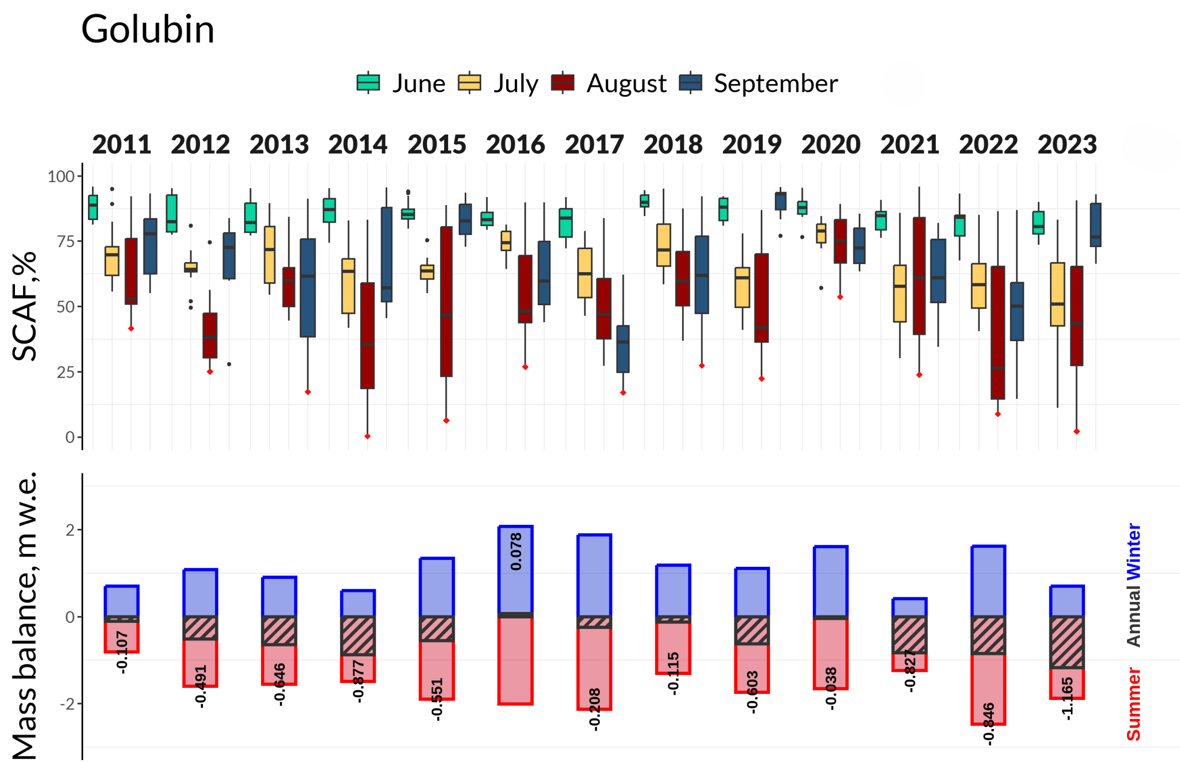

Figure 5: [corresponds to Figure E1 in the revised manuscript] Panel A shows monthly SCAF as a boxplot for Golubin glacier. The red point is the end-of-season SCAF. Panel B displays the corresponding measured annual mass balance (dashed line), accumulation (blue), and ablation (red).

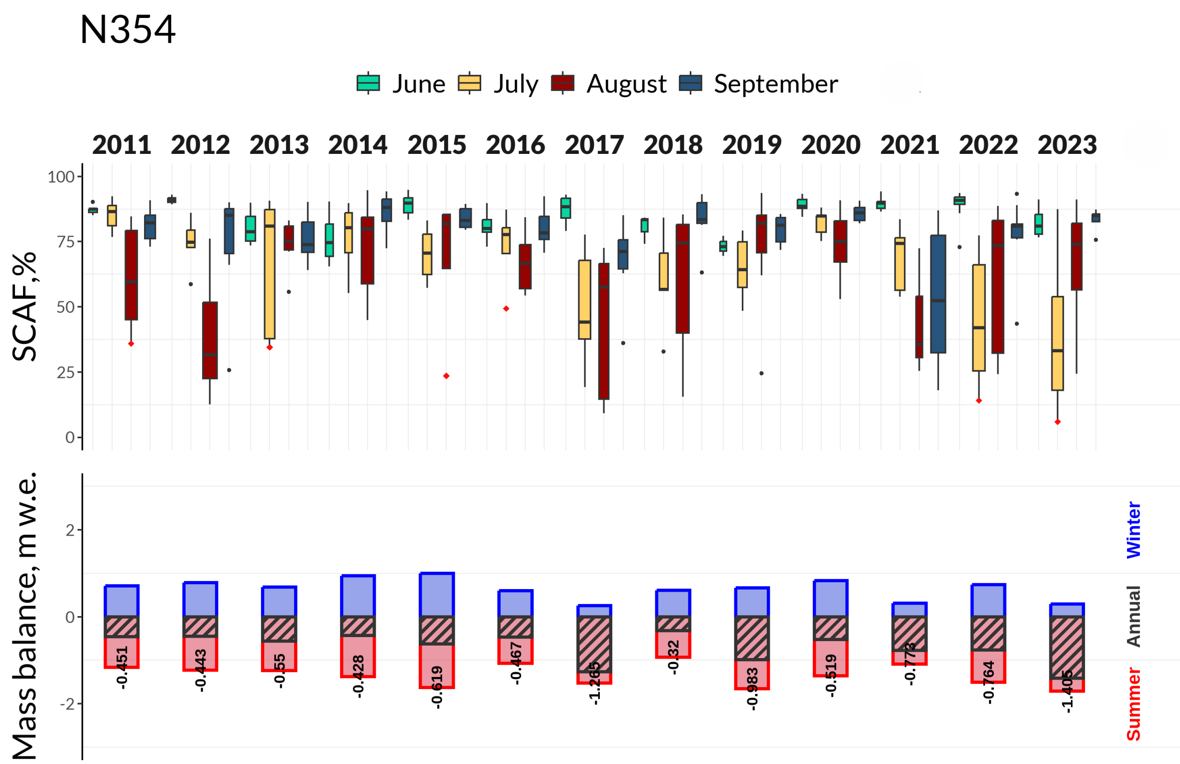

Figure 6: [corresponds to Figure E3 in the revised manuscript] Panel A shows monthly SCAF as a boxplot for Glacier No. 354. The red point is the end-of-season SCAF. Panel B displays the corresponding measured annual mass balance (dashed line), accumulation (blue), and ablation (red).

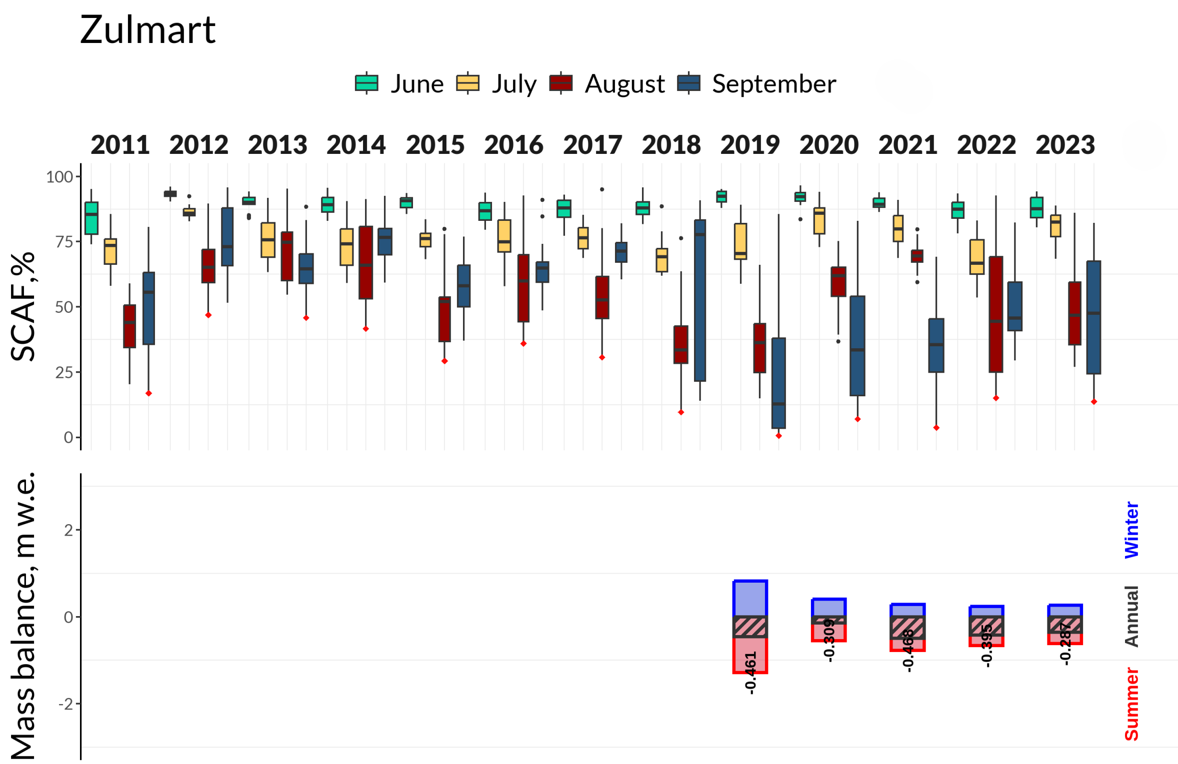

Figure 7: [corresponds to Figure E4 in the revised manuscript] Panel A shows monthly SCAF as a boxplot for Zulmart glacier. The red point is the end-of-season SCAF. Panel B displays the corresponding measured annual mass balance (dashed line), accumulation (blue), and ablation (red).

L117: Without more information, I don't think the mass balance data should be reported to three decimal places (for all glacier descriptions and Fig. 9).

We completely agree, and the decimal places are now reduced to two in the revised manuscript.

L107: L120: Chu River

This is changed accordingly throughout the revised manuscript. Thank you.

L153: ". ." typo

This is changed accordingly in the revised manuscript. Thank you.

L153: Can you quantify how many less images? What are the implications? Do you have a minimum number of images required to run the analysis?

The more images, the more overlap between the two sensors, the more robust the relation. However, the most important aspect is to obtain a good distribution from a SCAF = 0% to a SCAF = 100%. For Glacier No. 354, a reduced number of available images is visible on Figure 3 and in Figure Appendix A1. From Figure 3, it becomes evident that very few images are available for a SCAF between 50-70%, which surely limits the quality of the regression of this glacier in comparison with the other glaciers. However, considering that we have frequent observations for the remaining SCAF distribution and that we obtain a similar relationship than that for the other glaciers (new Figure added in the Appendix 8, we are confident that sufficient observations are available for the method we propose here. Instead of highlighting the fewer images for the regression calculation for glacier No. 354, we have added a Table 3 in the Appendixes that presents the number of MODIS-derived SCAFs obtained for each glacier, the number SCAFs obtained from S1 and S2 scences, and the number of pairs meanNIR S1/S2 SCAFs used. Even though we are not able to provide a minimum number of images, we have changed the wording in the revised manuscript and made sure to add a few words on the frequency and distribution of the SCAF observations in the Discussion section.

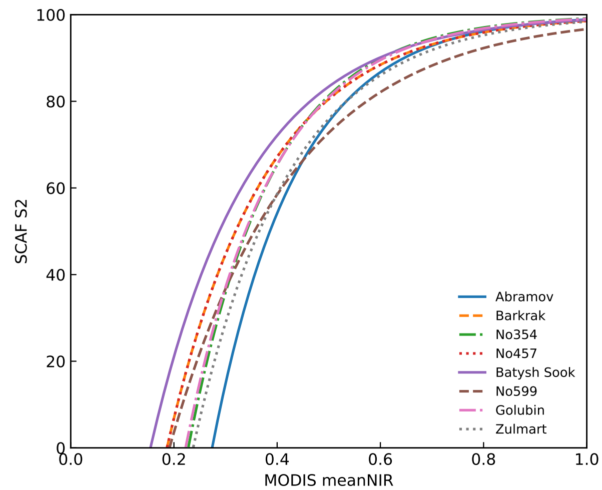

Figure 8: [corresponds to Figure C2 in the revised manuscript] Exponential regression function to obtain SCAF for eight different glaciers. Each glacier-specific regression was calculated using all available pairs of MODIS meanNIR and SCAF S1 & S2 from 2016 to 2023. differences in the regression are especially large when the snowline starts to rise higher on the glacier.

Study sites and data: The Appendix Figure A1 provides the summary on the temporal coverage and frequency of revisit of the satellite missions used for the SCAF estimation and for validation, and Table A1 presents the total number of MODIS-derived SCAFs, the amount of S-1 and S-2 images processed, and the number of couples meanNIR and S1/S2 used to build the regression per glacier.

Discussion: In order to draw a robust relationship across the full range of possible SCAFs, a good distribution of observations throughout the melt season is more important than the total quantity of images. Similar findings have been presented in Barandun et al. (2018).

Table 3: Number of generated MODIS-derived SCAFs, processed S1 and S2 images, and overlapping image pairs to build the regression between meanNIR and S1 and between meanNIR and S2

Site	MODIS-derived SCAF	After filtering	S1	S2	meanNIR-S1	meanNIR-S2
Abramov	1949	1682	85	200	29	158
Golubin	1813	1581	42	117	14	120
No. 354	1051	902	43	42	12	27
Zulmart	2092	1848	43	93	19	74

L159: Version 6.1, not 61

This is changed accordingly in the revised manuscript. Thank you.

L176: Description of S1A/B/C similar to the S2 description? Also, is it ascending/descending data? What are some of the challenged with SAR in mountains?

The description of the S-1 and S-2 datasets is now streamlined in the revised manuscript to provide a more consistent level of detail. We also specify the S-1 acquisition geometry (ascending and/or descending, as applicable). Furthermore, both the Methods and the Discussion sections are now expanded to better describe the limitations of SAR observations in mountainous terrain. In particular, we discuss terrain-induced effects such as radar shadow, layover, and foreshortening, as well as the sensitivity of C-band SAR to wet snow, while dry snow remains largely transparent to the radar signal.

Study sites and data: S-1 operates two near polar sun-synchronous orbit satellites at low Earth orbit with a 6-day revisit (as constellation). Both satellites feature a synthetic radar aperture (SAR) instrument onboard at the central frequency of 5.407 GHz (C band). The collected data is weather independent, which is an advantage for glaciers with persistent cloud cover during the summer. Continuous data collection over the study region started in April 2017 with 12-day revisit time. If several orbits cover the glacier, the revisit time is reduced to 5-7 days. According to the glacier orientation, we use the ascending mode for Abramov and the descending mode for all other glaciers. We use all available Level-1 ground-range-detected (GRD) data. These are radiometrically calibrated, multilook SAR images projected to ground range that provide backscatter intensity but no phase information. GRD data were selected because the wet-snow classification in our study is based on backscatter intensity and therefore does not require interferometric phase information. The interferometric-wide (IW) swath mode is acquired in dual polarization VV and VH over Central Asia and features the spatial resolution of 20 m at ground range and 22 m in azimuth direction resampled on a 10 × 10 m grid.

Methods: C-band SAR backscatter is highly sensitive to the liquid water content in the snowpack. While melt water is usually running off the impermeable glacier ice, melt water percolates and can saturate the snow. In presence of liquid water, the dielectric constant of the snowpack is highly reduced, leading to a higher absorption coefficient in wet snow. As a result, the penetration depth in SAR C-band decreases from around 20 m for dry snow to a few centimeters for wet snow, with most of the signal being absorbed or reflected by the upper layers of the snowpack, leading to a substantial decrease in backscatter over wet snow (Nagler and Rott, 2000; Marin et al., 2020; Buchelt et al., 2022). In contrast, dry snow remains nearly transparent to the SAR signal, and the backscatter is dominated by firn and glacial ice below the snow. Its larger grain size and the often high surface roughness of glacial ice lead to increased backscatter values in both cross- and copolarization. This results in pronounced contrasts of the backscatter signal between wet snow and dry snow but also glacial ice, which can thus be used to map the different surface properties. This contrast in the backscatter intensity between wet-snow and snow-free/dry snow-covered surfaces is the basis of the well-established approach in Nagler et al. (2016) to detect wet snow. On a glacier surface, three different surface types can be expected during the melt season along an altitudinal gradient (cf. Zhou et al., 2022): (i) bare-ice zone: low-elevated snow-free areas covered with glacial ice show high backscatter intensity; (ii) wet-snow zone: higher elevated areas (still) covered with melting (wet) snow show low backscatter intensity; (iii) frozen-percolation zone: upper parts of the glacier with completely frozen (dry) snow show high backscatter due to the underlying coarse-grained firn and glacial ice. Consequently, the boundary between (i) bare glacial ice and (ii) melting wet snow on a glacier detected by the difference in SAR backscatter intensity can thus be used as a proxy for the transient snowline (Winsvold et al., 2016). In case of absent wet snow (e.g., during cold spells causing the snowfall of fresh dry snow or refreeze), this approach is not able to accurately detect a transient snowline. Therefore, the approach is limited to the main snow-melt period. To identify the SCAF, we first identify the wet-snow area. All glacial area elevated above the wet-snow area is then assumed to be covered by dry snow and included in the SCAF.

Discussion: Although S-1 images are not affected by clouds, dry snow is transparent in the C band (Nagler et al., 2016), which excludes accurate capture of summer snowfalls and the end-of-season snowline. Also, a fixed threshold of -6 dB for wet-snow detection is applied here, which is not necessarily optimal for all the study glaciers throughout the ablation season due to the differences in climatic settings, sensor viewing angle, and polarization (Winsvold et al., 2018; Buchelt et al., 2022). Besides, steep terrain could lead to radar layover and shadow effects; however, this issue is limited to very small parts at the study sites. Nevertheless, S-1 can provide valuable snowline observation information independently (see Fig. 4). However, the potential of S-1 imagery is not fully revealed in the present work as this is only used as a backup in case of unavailable or cloud-obscured S-2 acquisitions. In addition, the limitation of S-1 to the main ablation period results in the necessity to always include cloud-free optical images. Thus, the benefit of S-1 is limited for the proposed application as long as enough reliable cloud-free S-2 acquisitions are available.

L178: replace "imagery" with "data"

This is changed accordingly in the revised manuscript. Thank you.

L179: A stronger description of what GRD data is and what is it used for would be helpful.

The description of the S-1 GRD product is now expanded in the Methods section of the revised manuscript. In particular, we briefly explain that ground-range-detected (GRD) products are radiometrically calibrated, multilook SAR images projected to ground range that provide backscatter intensity but no phase information. We also clarify why GRD data were selected, namely because the wet-snow classification in our study is based on backscatter intensity and therefore does not require interferometric phase information.

Study sites and data: We use all available Level-1 ground-range-detected (GRD) data. These are radiometrically calibrated, multilook SAR images projected to ground range that provide backscatter intensity but no phase information. GRD data were selected because the wet-snow classification in our study is based on backscatter intensity and therefore does not require interferometric phase information.

L185-189: Are these polygons or lines? i.e. is it just the snowline being digitized or is it the SCA.

It is the SCA; we clarify this in the revised manuscript.

Study sites and data: To validate our automatic mapping tool, we use SCAFs derived from manually delineated snowlines from independent Landsat imagery from Barandun et al. (2018, 2021) that span between 2000 and 2016 for Abramov, Golubin and Glacier No. 354. These data have been published in Barandun et al. (2015, 2018); Azisov et al. (2022); Kronenberg et al. (2016). We calculate SCAFs for Zulmart in the same way.

L187-188: Can you discuss more about the manual datasets that you created? Perhaps in a supplement? Which dates, what did you do for clouds, etc.

The outlines have been delineated manually using ArcGIS. Most of these data have already been published, and we refer the reader to the relevant publication.

Study sites and data: To validate our automatic mapping tool, we use SCAFs derived from manually delineated snowlines from independent Landsat imagery from Barandun et al. (2018, 2021) that span between 2000 and 2016 for Abramov, Golubin and Glacier No. 354. These data have been published in Barandun et al. (2015, 2018); Azisov et al. (2022); Kronenberg et al. (2016). We calculate SCAFs for Zulmart in the same way. We download all available Landsat images from 2018 to 2023, then manually map the snow-covered area on ArcGIS and use the RGI outlines to calculate the SCAF for each scene.

L190-191: This is a big issue. Having the outlines constant and using the meanNIR of the glacier presents a potentially large error that increases over time. As the glacier retreats, more land is exposed, lowering the meanNIR value of the polygon substantially. I think this requires more explanation and sensitivity analysis. This is likely somewhere ML methods would outperform Otsu.

Please refer to the answer provided above for the corresponding general comments. As abovementioned, the revised manuscript now includes a sensitivity analysis to assess the influence on 1) the meanNIR and 2) the SCAFs, in which we show that the effect is minimal.

Discussion: Throughout the entire study period, We use fixed glacier outline from GLIMS and RGI v6. As glaciers retreat, the fraction of snow within fixed glacier area reduces over time, exposing bed rock or sediments at the surface. Additionally, the geometry of the glacier and the orientation of its tongue can change over time (Khromova et al., 2014). When assessing whether the use of a static glacier outline may introduce significant bias, a maximum theoretical error of less than 2% for the MODIS mean NIR reflectance and 1.4% for the S-2 SCAF calculation was obtained (see Appendix D). Both values are conservative upper bounds, and the actual errors are expected to be considerably smaller; an example is shown in Figure 2. We therefore conclude that the use of static RGI outlines does not significantly affect the results of this study.

L221: Not sure I would characterize S1 and S2 as "high resolution". I'm assuming that's what is being referred to here. Perhaps use "higher resolution" or simple "S1 and S2"... This comes up a few times in the manuscript. Please find more appropriate terminology and correct throughout, as "high resolution" has a definition in remote sensing. (e.g. L298)

This is changed accordingly in the revised manuscript. Thank you.

L234-235: This statement depends on the size of the glacier. MODIS is sufficient resolution for a large enough glacier.

We rephrase the statement in the revised manuscript to highlight that, for the glacier studied here, MODIS is too coarse to study the snow-covered area directly.

Methods: As the spatial resolution of MODIS is too coarse for a direct pixel-wise snow-cover classification for most mountain glaciers in the Tien Shan and Pamir, we calculate the mean reflectance value over the total glacier area instead.

L236: Not sure what is meant here. Is there a fixed distance buffer (e.g. 500m)? It seems like a lot of non-glacier pixels are going to be included (pixels must contain 65% of the 1.4x larger polygon). This may exacerbate the issue listed in the first major comment.

We do appreciate that this section is unclear. We clarify and better justify our choice in the revised manuscript. The buffer is selected in relation to the glacier size. From this buffered area, pixels that contain less than 65% of the rigid outline are excluded. Since this area is constant over the entire study period, it does not affect the SCAF mapping.

Methods: To include all relevant MODIS pixels, we create a buffer around each glacier. The buffer area is approximately 1.4 times the original glacier area. All pixels covering less than 65% of the buffered area are excluded. The purpose of the buffer is to account for small geolocation inaccuracies, ensuring that pixels near the glacier boundary are not inadvertently excluded from the analysis.

L240: In cases when there are 3 or less cloudy pixels, are they masked out, or kept? The wording is unclear.

In the instances in which the clouded pixels are less than 3, these are kept; otherwise, they are masked out. We rephrase this in the revised manuscript to make sure it is absolutely clear.

Methods: The scenes that contain more than 3 cloudy pixels per glacier are removed from the analysis.

L245: What does this algorithm do? Please explain briefly. Seems the referenced paper developed it for forested terrain?

We expand the description of the applied topographic correction in the revised manuscript. In particular, we briefly explain that the modified sun-canopy-sensor correction (SCS+C) is used to reduce terrain-induced illumination effects caused by varying slope and aspect, thereby improving the consistency of the S-2 surface reflectance prior to snow classification. We also clarify that, although the method was originally developed for forested terrain, it is applied here to account for topographic illumination effects in mountainous terrain.

Methods: SCS+C is used to reduce terrain-induced illumination effects caused by varying slope and aspect, thereby improving the consistency of the S-2 surface reflectance prior to snow classification. Although the method was originally developed for forested terrain, it is applied here to account for topographic illumination effects in mountainous terrain.

Section 3.1.1: Please explain what happens to adjacent rock in this workflow. I assume they are groups in with "ice". This limitation should be very clearly articulated

Mapping is only performed within the glacier outline. The area that melts at the glacier tongue is indeed classified as ice; however, the effect is minimal for the SCAF as now shown in the sensitivity analysis. We answer this in more detail in the general comment and discuss it further in the revised manuscript.

Methods: The ice-free surface that is exposed by the retreating glacier at the glacier tongue is classified as ice for all sensors. In the Appendix D, we show that the effect of the changing outlines is negligible for our study period and sites.

Discussion: When assessing whether the use of a static glacier outline may introduce significant bias, a maximum theoretical error of less than 2% for the MODIS mean NIR reflectance and 1.4% for the S-2 SCAF calculation was obtained (see Appendix D). Both values are conservative upper bounds, and the actual errors are expected to be considerably smaller; an example is shown in Figure F2. We therefore conclude that the use of static RGI outlines does not significantly affect the results of this study.

L251-252: Unclear how thresholds were selected. Seems arbitrary. If they were selected manually, what dates were used? What are the implications of using different thresholds on each glacier, between seasons, and over time?

The Otsu threshold method has been applied in Rastner et al. (2019) on a wide range of glaciers and provided suitable results. The Otsu method automatically performs clustering-based image thresholding on each image individually by assuming that the image contains two classes (snow and ice) and has thus a bimodal histogram. Rock or, in our case, debris on the tongue is usually classified as ice and thus would not affect our classification. More details are provided in Rastner et al. (2019). The optimum threshold for separating the two classes is found when their combined spread is minimal or their interclass variance is maximal. Choosing the correct threshold becomes difficult when the entire glacier is snow covered or the snowline rises above the firn line. To avoid a wrong classification, for such cases a minimum and maximum threshold values are introduced for each glacier based on manual inspection for a range of SCAF between 0% and 100%. If an automatically detected threshold lies outside this range and thus no optimal threshold can be found, a fixed threshold is assigned. This fixed value is also manually selected. We include an example (Fig. 9) and the results from a sensitivity analysis in the Annexes of the paper and clarify the threshold choice in the Methods section.

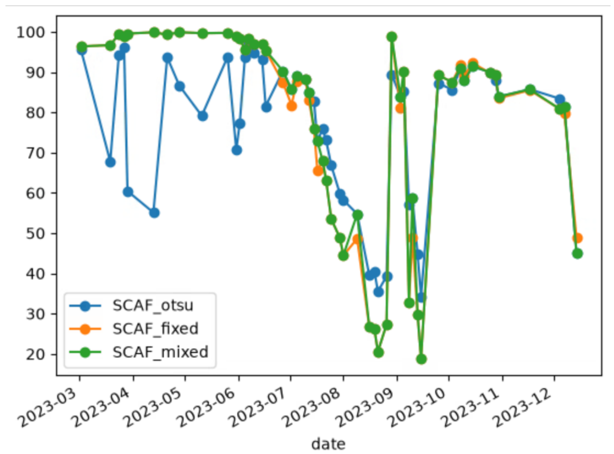

Figure 9: [corresponds to Figure B2 in the revised manuscript] Comparison of SCAF mapping for Abramov from 2023 using an unbound Otsu threshold (blue), a fixed threshold (orange), and the method presented here (green) using a fixed threshold when the automatically selected threshold falls outside of the minium and maximum range that slightly improves the classification results. The Otsu threshold method fails at the beginning of the season when the entire glacier is completely snow covered, at the end of the melt period when the snowline rises above the firn line, and in midseason when cast shadows disturb the bimodel curve.

Methods: The main purpose of the classification algorithm is to differentiate between snow-covered and snow-free surfaces. We use the NIR channel reflectance values and apply the Otsu-threshold algorithm (Otsu, 1979) to distinguish snow-covered areas similarly to what is done in Rastner et al. (2019). The Otsu algorithm is designed to find the optimal threshold (th) for each glacier and scene by maximizing the interclass variance between two classes on the image, assuming bimodal distribution on the frequency histogram (here, snow and ice). We have identified three cases in which the Otsu threshold method fails: (i) under completely snow-covered conditions, (ii) when the snowline is above the firn line, and (iii) when cast shadows from clouds are present (Fig. B2). In such cases, the frequency distribution is not clearly bimodal. Thus, an unbound threshold can misrepresent the snow condition over the glacier area. To mitigate this, we defined th_{min} and th_{max} to determine the range of validity for using a threshold determined by the Otsu algorithm. If the initially detected threshold lies outside the predefined th_{min} and th_{max} range, a fixed threshold (th_{fixed}) is applied instead to classify the image. The range $th_{min} < th < th_{max}$ as well as the fixed thresholds are manually identified after comparing classified images with the RGB composites of each glacier to improve classification (Table 3). The same set of thresholds (th_{min}, th_{max}, and th_{fixed}) is applied to the entire time series of preprocessed S-2 imagery per glacier and it is only applied when automatic thresholding fails (thus generally under completely snow-covered or snow-free conditions or cloud shadowing).

L256: Information missing in "(3)".

It refers to Table 3; it has now been corrected. Thank you.

L261: How is the total number of glacier pixels determined? (static over time from RGI?)

We clarify this in the revised manuscript. Yes, it is static over time. This is a shortcoming of the method since it will overestimate the glacier area towards more recent years. We address this in the general comment and show that the effect is not significant for our study sites and period.

Methods: SCAF S2 is calculated as a proportion of snow-covered pixels on the glacier to the total number of glacier pixels from the RGI outlines after a snowline altitude (SLA) correction (see Sect. 3.1.5).

L266-267: What about ice? How does radar interact with ice? It is not clear how the S1 data is being used and if it is accurately identifying the snowline, as L278 suggests.

We agree that the current description of the S-1 methodology is too brief. Therefore, this part is expanded on the revised manuscript to better explain the physical basis of the approach. In particular, we describe the radar interaction with wet snow, dry snow, and bare ice, emphasizing the pronounced contrast in C-band backscatter between wet snow and the surrounding dry snow or bare ice. We further clarify that the approach exploits the temporal evolution of the SAR backscatter during the melt season, as melt-induced changes in liquid water content and surface conditions provide a distinct signal that enables the tracking of the transient snowline.

Methods: C-band SAR backscatter is highly sensitive to the liquid water content in the snowpack. While melt water is usually running off the impermeable glacier ice, melt water percolates and can saturate the snow. In presence of liquid water, the dielectric constant of the snowpack is highly reduced, leading to a higher absorption coefficient in wet snow. As a result, the penetration depth in SAR C-band decreases from around 20 m for dry snow to a few centimeters for wet snow, with most of the signal being absorbed or reflected by the upper layers of the snowpack, leading to a substantial decrease in backscatter over wet snow (Nagler and Rott, 2000; Marin et al., 2020; Buchelt et al., 2022). In contrast, dry snow remains nearly transparent to the SAR signal, and the backscatter is dominated by firn and glacial ice below the snow. Its larger grain size and the often high surface roughness of glacial ice lead to increased backscatter values in both cross- and copolarization. This results in pronounced contrasts of the backscatter signal between wet snow and dry snow but also glacial ice, which can thus be used to map the different surface properties. This contrast in the backscatter intensity between wet-snow and snow-free/dry snow-covered surfaces is the basis of the well-established approach in Nagler et al. (2016) to detect wet snow. On a glacier surface, three different surface types can be expected during the melt season along an altitudinal gradient (cf. Zhou et al., 2022): (i) bare-ice zone: low-elevated snow-free areas covered with glacial ice show high backscatter intensity; (ii) wet-snow zone: higher elevated areas (still) covered with melting (wet) snow show low backscatter intensity; (iii) frozen-percolation zone: upper parts of the glacier with completely frozen (dry) snow show high backscatter due to the underlying coarse-grained firn and glacial ice. Consequently, the boundary between (i) bare glacial ice and (ii) melting wet snow on a glacier detected by the difference in SAR backscatter intensity can thus be used as a proxy for the transient snowline (Winsvold et al., 2016). In case of absent wet snow (e.g., during cold spells causing the snowfall of fresh dry snow or refreeze), this approach is not able to accurately detect a transient snowline. Therefore, the approach is limited to the main snow-melt period.

L276: How is the -6db threshold decided, please elaborate (examples, supplement, compare to other work, etc.)

This was the choice of the late main author after a careful analysis of different threshold values and was based on expert knowledge. Unfortunately, we do not have more information on this choice.

Methods: We found a threshold of -6 dB to be suitable, based on the visual inspection of the scenes of the different mountain glaciers.

L277: What method was used to resample the data?

We used the spatial mean for resampling the data. We added this information in the respective part of the revised manuscript.

L297: change "the" to "a linear function"

This is changed accordingly in the revised manuscript. Thank you.

L307-308: Unclear why this is necessary? What situations would cause this, please give an example. Also, how many images are removed due to this?

This filter was used to remove outliers from the time series. It affects about 10% of all MODIS scenes. We rephrased to make it clearer and listed the number in Table 3.

Methods: To be on the conservative side and only keep reliable SCAF values, we exclude unrealistic values that deviate by more than 1.5 standard deviations below the annual mean SCAF from SCAF time series from the $glacierSCAF_{MODIS}$ algorithm (Table A1).

Figure 3: Can the Landsat validation data be added here as well?

We add Landsat validation observations where overlapping with the S1 and S2 data. Unfortunately only a few Landsat images overlap exactly with the MODIS acquisition date.

Figure 3: Not convinced that S1 is contributing much here. Also, why so few data points from S1?

We understand the reviewer's comment and address this in more detail in a later section of the revised manuscript. Please also see the response in the general comment. Indeed, the S1 data do not provide any significant benefit. Only a few images are provided here because these are the only ones that overlap with sufficient quality the MODIS survey and there is no better S2 image available.

Figure 3: Is this only a single year of data? If so, which year? Do you have different curves for every year?

The relationship was established only once per glacier, incorporating all observations that overlapped between the MODIS and the S1/S2 acquisition times throughout the entire Sentinel lifespan. This is clarified in the text, and the caption is extended in the revised manuscript.

Methods: To build a regression model for each glacier separately, we select all the dates with observations available for both MODIS meanNIR and SCAF S1 & S2 combined time series from 2016 to 2023.

and

Figure 3: Exponential regression function to obtain SCAF for four studied glaciers. Each glacier-specific regression is calculated using all available pairs of MODIS meanNIR and SCAF S1 & S2 from 2016 to 2023.

L328: "in 4" should be "in Fig. 4" ?

This is changed accordingly in the revised manuscript. Thank you.

L330-331: I'm not sure the wording of MODIS being more accurate is correct here. Landsat is the "validation" so how can you say MODIS is more accurate if it underestimates your validation dataset? Do you mean the higher temporal resolution allows a more precise determination of the end-of-season SCAF?

We rephrase this statement in the revised manuscript. Indeed it means that the end of the season can be determined more accurately.

Methods: While MODIS-derived SCAFs are often lower than Landsat-based manual delineations (Sec. 2.3.1), MODIS's higher temporal resolution enables the end of the season to be identified more accurately, thanks to its higher image frequency throughout the entire melt season.

Figure 4: Hard to read x axis.

We improve the readability of this figure in the revised manuscript.

Figure 4: I thought S1 after August were removed?

Yes, they were removed for further analysis but shown here to highlight the issue with dry snow. We clarify this in the caption of the figure.

Figure 4: Glacier SCAF evolution during the melt season derived from MODIS-based SCAF, Sentinel-1, Sentinel-2, and manually from Landsat imagery for 2008 and 2018. Sentinel-1 (only images prior to mid August) and Sentinel-2 images from 2016 to 2023 are used to calculate the regression model to derive the MODIS-based SCAF from 2000 to 2023. Manually derived SCAFs from Landsat provide an independent validation of the regression model. Sentinel-1 and 2 perform well when snow is depleting; however, Sentinel-1 fails to appropriately map fresh snow fall (dry and fine layer of snow, e.g., for Glacier No. 354 at the end of the ablation season).

Figure 5: Can this bias be explained because the glacier outlines are static? So over time more rock is exposed and the meanNIR is darker than if only snow and ice are incorporated?

This is not the case. The outlines of the glaciers were also kept constant in the Landsat mapping. Please also see the answer to the general comment, where we show that the effect of the constant outline is minimal for our study.

Figure 6: Nice figure! A bit small and hard to dig into, but very nice way to communicate this. Perhaps remove the early season, that way the main summer months can be seen more clearly? Also, please change the black boxes. It is misleading as the color black is in your color ramp as well.

We remove the black boxes in the revised manuscript. However, we would like to keep the early season, as this is important to observe changes in the onset of snowmelt and its variability both over time and from glacier to glacier.

L362-L365: This may be easier to visualize in a line graph of the data in Fig 6

We would prefer not to add any additional figure to the manuscript; therefore, a figure is included in the Annexes (Fig 10).

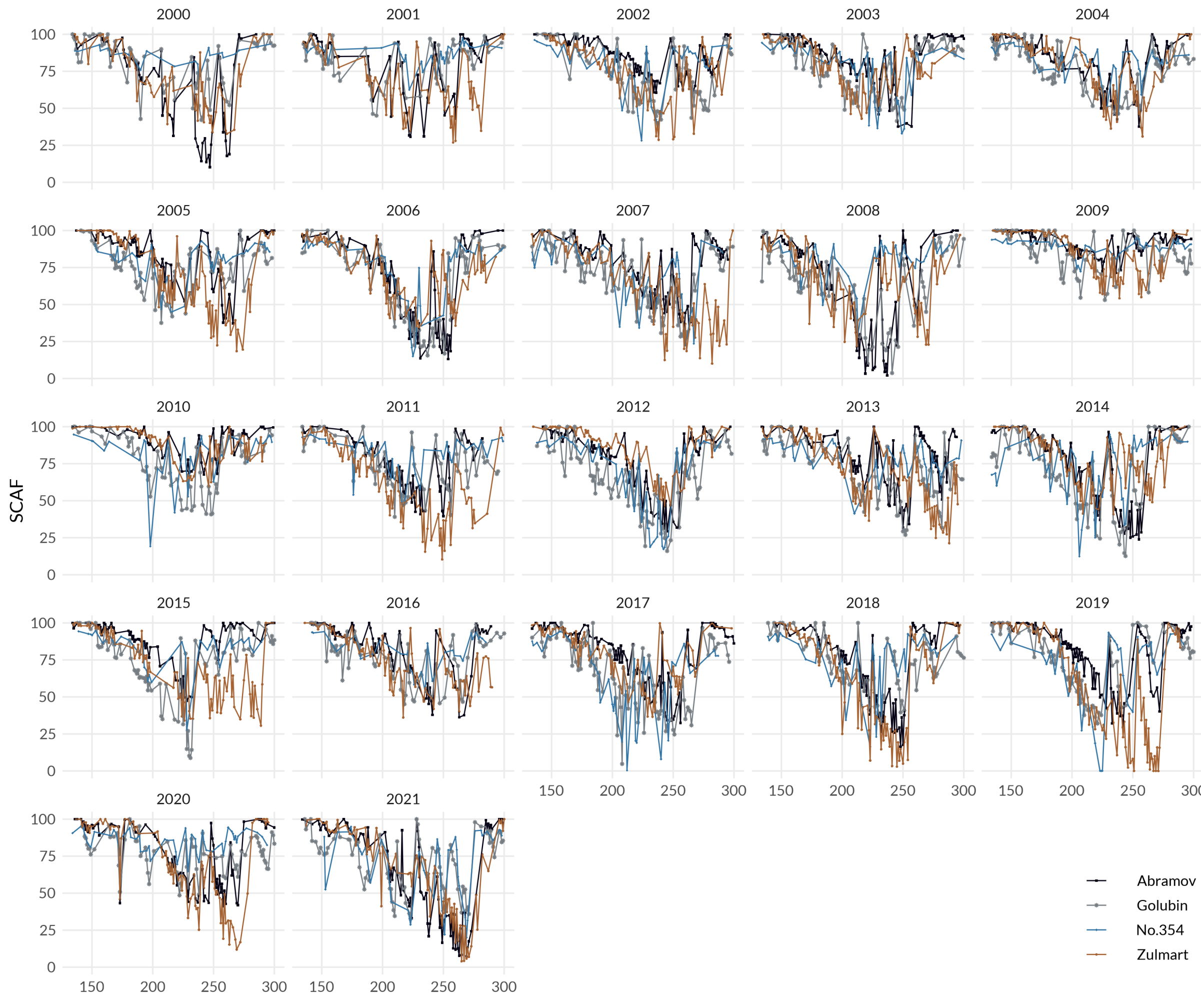

Figure 10: [corresponds to Figure D1 in the revised manuscript] Subseasonal SCAF time series for each glacier and year from 2000 to 2021

Figure 7: Is it possible to add a metric of uncertainty in this graph? Perhaps the number of images in that year? Also, perhaps the min SCAF. So that we may see if the longer seasons are related to the lower SCAF.

We rework this figure accordingly in the revised manuscript.

L379: annual snowline rate of change or annual SCAF rate of change?

This corrected in the revised manuscript to annual SCAF rate of change.

L391: The "annual" surface mass... ?

This is changed accordingly in the revised manuscript. Thank you.

L379: L439: SCAF or snowline? I think you mean SCAF?

Yes. The reviewer is absolutely right. Thank you for noticing. This is of course corrected to SCAF here and throughout the manuscript in the revised version, and we apologize for the confusion.

L455: Not clear how figure B1 relates to this comment of decreased meltwater in autumn.

The figure reference is corrected in the revised manuscript.

L505: Not the "same", but similar? What is different about these curves? can they be generalized or can the coefficients be predicted?

We rephrase it in the revised manuscript. The curves need to be calculated individually for each glacier. The glacier response to changes in climatic settings reflected through its relationship to the snowline can differ greatly from one glacier to another depending on its regime and geometry. We have decided to include some additional explanations regarding this and a figure in the Appendixes comparing the different regressions (Appendix Fig. 8).

Discussion: The exponential relation between MODIS meanNIR over the glacier and SCAF S1 & SCAF S2 persists for all the studied glaciers (Fig. 3). Further testing on other glaciers in the region reveals the similar exponential relationship (Appendix Fig. B1) and underlines the robustness of the here proposed methods. The seasonal SCAF time series thus represents the snow depletion patterns on the glacier during the melt season (Fig. 4). While all glaciers follow the same exponential relationship, the fitted coefficients are strongly dependent on glacier-specific geometry, size, and mass balance sensitivity, resulting in considerable variability in the derived MODIS-based SCAF values. Consequently, a glacier-specific parameterization is necessary for accurate results (Appendix Fig. C2).

Figure 10: Nice figure, but not sure what is learned here?

This figure shows the importance of including subseasonal snowline observations provided by the proposed methodology in glacier mass-balance assessments. We further highlight in the revised manuscript the value of such auxiliary data for glacier monitoring strategies as well as mass balance modeling, especially for data-sparse regions. We extend the figure caption in the revised manuscript to make it clearer that this provides a unique tool to validate subseasonal glacier model performance and hence daily melt water release estimates:

Figure 10: Modeled SCAF (red) and MODIS-based SCAF (blue) for the Abramov glacier from 2012 to 2023 (top row of each panel), with annually calibrated cumulative melt (black line, right axis). Modeled SCAF is derived from the mass balance model calibrated to annual glaciological observations (Sect. 2.3.5); RMSE provides model performance against these observations for each year. Gray shading marks the critical period of fastest snowline change, over which the rate of SCAF change is calculated (red: modeled; blue: observed). The bottom row shows average daily air temperature. Comparing modeled and observed SCAF validates the subseasonal performance of

the modeled mass balance and melt rates, which are key to understanding glacier meltwater contribution to river runoff and its relation to air temperature. Snow depletion is often modeled too fast during the critical period, with excessive melt compensated by too much snow accumulated during winter.

We also include a better explanation in the text:

Results: The modeled SCAF during the summer months shows a snow depletion pattern similar to that of the retrieved time series from MODIS (Fig. 10). For the Abramov glacier, summer snowfalls as well as the end of season are well approximated by the model. Drops in air temperature often show a slowdown of SCAF changes and often relate to summer snowfall events (Fig. 10; e.g., 2014). Despite the limited accuracy of the precipitation dataset (ERA5) (Zandler et al., 2019; Dollan et al., 2024), the model captures well the seasonal snowline evolution during the summer. However, we notice two important tendencies in the predicted modeled daily SCAF: 1) the modeled SCAF is overestimated by the model, especially in earlier years (e.g., 2013), and 2) snow depletion tends to be too fast and abrupt during July to August (critical period for meltwater release, e.g., 2020), despite a good agreement of the modeled annual mass balance with annual mass balance observations (Fig. 10). This indicates that, despite good end-of-season RMSE, the model's subseasonal performance and its ability to resolve freshwater availability are limited when no subseasonal calibration data, such as the SCAF time series presented here, are available.
In this model, melt rates are low at the beginning of the season, accelerate in mid-July, peak between late July and mid-August, and drop again in September. However, the SCAF depletion observed in the remote sensing data evolves more gradually, especially during July and August, suggesting more moderate meltwater production during the summer months than that simulated by the melt model, which describes an empirical relationship between air temperature and the melt of snow and ice (see Sect. 2.3.4).
[. . .]
While it might not influence the annual estimate of surface mass balance change or the total annual melt water release, it becomes crucial to understand the daily meltwater input during the dry summer months and the potential future runoff changes for Central Asia (Barandun et al., 2020).

L542-547: Unclear how useful S1 was in this study? Would the results be much different if S1 was not used?

Please refer to the answer to the general comment. We agree with the reviewer and discuss this more clearly in the revised manuscript. We however believe that retaining the S-1 component strengthens the methodological evaluation of the proposed approach, even though excluding it would likely have only a minor impact on the final MODIS-derived SCAF time series of this study.

Discussion: Although S-1 images are not affected by clouds, dry snow is transparent in the C band (Nagler et al., 2016), which excludes accurate capture of summer snowfalls and the end-of-season snowline. Also, a fixed threshold of -6 dB for wet-snow detection is applied here, which is not necessarily optimal for all the study glaciers throughout the ablation season due to the differences in climatic settings, sensor viewing angle, and polarization (Winsvold et al., 2018; Buchelt et al., 2022). Besides, steep terrain could lead to radar layover and shadow effects; however, this issue is limited to very small parts at the study sites. Nevertheless, S-1 can provide valuable snowline observation information independently (see Fig. 4). However, the potential of S-1 imagery is not fully revealed in the present work as this is only used as a backup in case of unavailable or cloud-obscured S-2 acquisitions. In addition, the limitation of S-1 to the main ablation period results in the necessity to always include cloud-free optical images. Thus, the benefit of S-1 is limited for the proposed application as long as enough reliable cloud-free S-2 acquisitions are available.

L548: More discussion about the reliability of this method. The validation shows RMSE between 14-25%.

Given the nature of the input data, we consider the method to be reliable within the expected uncertainty. The issue of many areas remaining ambiguous is present even when mapping snow-covered areas manually on satellite images, and the process still relies heavily on expert knowledge. Such areas include slush, superimposed ice, and refreezing crusts, to name a few. An additional complication arises when the snowline rises above the firn line. Uncertainties in mapping are higher for lower SCAFs. In Barandun et al. (2018), an experiment was conducted to classify manually the minimum and maximum possible snowlines, depending on whether ambiguous areas were classified as snow or ice. The differences were particularly significant around the median elevation of the glacier. The same study estimated the uncertainty of automatic mapping of Landsat images to be 8–13% compared with manual mapping. This result is slightly better than our findings, which is not surprising given the higher resolution of the Landsat images used for mapping compared with that of the MODIS-derived SCAF used in the present work. The paragraph appears now in the revised manuscript as follows:

Results: We compared the SCAFs derived from $glacierSCAF_{MODIS}$ with the SCAFs manually derived from Landsat (Fig. 5). Abramov glacier, Glacier No. 354, and Golubin glacier exhibited an RMSE below 20%. For these three glaciers, the $glacierSCAF_{MODIS}$ results are systematically underestimated by an average of 16%. Visual inspection of the corresponding Landsat scenes indicates that the variation is greatest within the 50–65% SCAF range. This range is close to the median elevation of the glacier, and in the case of the three glaciers, it is an area prone to ambiguous surface types, such as slush, superimposed ice, and refreezing crust formation. SCAFs at around 30% are close to the firn line. When the snowline rises above the firn line, the distinction between firn and snow becomes extremely difficult, even for manual mapping. Zulmart glacier shows slightly less good agreement, with an RMSE of 25%. SCAFs in the lower ranges (0–50%) are overestimated by an average of 19.7% on MODIS images. Superimposed ice and refreezing are frequent on Zulmart glacier. It is very difficult to correctly map bright refrozen meltwater, even with manual mapping.

L550-552: This is an important point that should have more attention, as I've mentioned a few times now.

Please refer to the answer to the general comment. We extend the Discussion section in the revised manuscript; however, as shown in our answer to the general comment, the effect of the constant outline does not influence our results significantly.

L555: space missing before Letréguilly.

This is changed accordingly in the revised manuscript. Thank you.

L561: I'm not sure "interrupted" is the correct word.

We rephrase this in the revised manuscript. Thank you.

L565-570: Would lag times be useful to look into here? I.e. could there be a delay in the response?

We are afraid we were not able to fully understand the reviewers comment and therefore cannot provide an answer at the moment.

L573-575: It would be nice to include these years in Fig C1. i.e. Years where SCAF = 0, what is the SMB doing?

These years cannot be included in Figure C1 because the snowline is no longer representative of the mass balance. The mass balance-snowline or SCAF relationship is usually taken to be linear. Once the SCAF is at zero, the theoretical ELA (approximated by the snowline as long as there is a snowline on the glacier) can exceed the maximum glacier elevation. Therefore, the relationship between the snowline and the mass balance is no longer valid. This is a significant limitation of this approach and the reason why we use SCAF observations to accurately represent modeled subseasonal mass balance rather than the end-of-summer SCAF as a proxy for mass balance.

Figure A1: Can S1 and S2 be separated?

We improve the figure in this respect in the revised manuscript.

Figure B1: x axis is crowded and formulas are truncated.

We improve the readability of this figure in the revised manuscript.

Figure C1: change -1 to superscript in x axis label. Figure not cited in document? Could be one of the "??"

We correct the axes and the referencing in the revised manuscript.

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2 Reviewer #2

2.1 General Comments

The accurate monitoring of sub-seasonal snowline migration is of great necessity since it could provide more detailed SMB dynamics as well as meltwater distribution over glaciers. This manuscript has made nice attempts in this aspect by obtaining close-to-daily SCAF information which could potentially indicate SMB. However, to be honest, I find it a little hard to understand this paper and the language must be further polished. Although the connection between SCAF from Sentinel-1/2 and MODIS NIR exhibits some novelty, the current description about methods seems not so convincing to me, and I have serious doubts about its availability. Unfortunately, I think the current manuscript could not meet the publication standards of this journal.

We would like to thank the reviewer for their feedback. We understand that the main criticism concerns the clarity of the paper, particularly in the Methods section. We have addressed each comment individually and added explanations to the manuscript to make it more convincing. Furthermore, we will have a proofreader correct the English language and sentence structure of the manuscript.

2.2 Major Improvement Needed

There are too many errors in citations and punctuation marks which cannot meet the standard of a high-quality paper, please carefully check. If you use LaTex, please carefully check.

We profusely apologize for all the errors in the references. We have carefully checked the manuscript and corrected all referencing errors relating to figures, tables, and citations, as well as all punctuation errors. Before resubmission, a professional proofreader will correct the manuscript to avoid any further errors and ensure good readability.

Since the topic is snowline dynamics, it is a bit strange that you did not mention anything about SLA in the Abstract, it is better to add some direct explanations. Another possible way is to change the title to snow-covered area as you demonstrate in Line 47.

We agree with the reviewer that the title is misleading, and we have changed it in line with reviewer #1 s comment.

Title: Subseasonal snow cover dynamics on four glaciers in Central Asia from multisensor satellite observations

In addition we reworded the Abstract, complying also with reviewer #1, an it reads now:

Abstract: Subseasonal glacier dynamics strongly influence the timing and magnitude of meltwater supply, a vital component of summer runoff in dry Central Asia. Understanding glacier snow cover evolution during the melt season is therefore essential to predict subseasonal water availability and glacier response to climate change. We present a novel method using multisensor satellite observations to infer subseasonal glacier snow-covered area fraction (SCAF; the ratio of snow-covered area above the snowline to total glacier area) over a 24-year period, with potential for regional-scale application. The method is developed and tested on four well-studied glaciers across the Pamir and Tien Shan mountains. Our approach combines medium-resolution MODIS with high-resolution Sentinel-2 optical and Sentinel-1 radar imagery to produce close-to-daily SCAF estimates throughout the melt season from 2000 to the present day. Validation against manually delineated Landsat snowlines yielded RMSE values below 20% for most sites. The resulting time series reveal substantial interannual and regional SCAF variability. Recent warm years show earlier bare-ice exposure and shifts in the end of the melt season of up to one month later. Accelerating snow depletion rates were identified for all four glaciers, beginning in 2000 or 2009 and reaching up to -1.25% of SCAF reduction per day. The SCAF time series were linked to annually measured and daily modeled glacier mass balances. Despite similar annual mass balance values, glaciers exhibited marked differences in subseasonal snow depletion and meltwater contribution, driven by different atmospheric conditions during the melt season. These findings demonstrate the value of long-term, high-temporal-resolution snowline monitoring for improving the understanding of glacier–climate interactions and constraining seasonal runoff forecasts in Central Asia's water-scarce river basins.

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The Introduction section can be streamlined, the current version contains too many unnecessary details, such as the in-situ observations during Soviet times.

The Introduction section is substantially modified in the revised manuscript; we shorten and streamline it. Changes respond also to the comments from reviewer #1. We agree that the Introduction section contained many unnecessary and nonrelevant details for the present study. Below, we show only the paragraphs of the Introduction that have undergone major changes.

Introduction: Almost all glacier monitoring programs in the former Central Asian Soviet Union states collapsed in the early 1990s, following the dissolution of the Soviet Union in December 1991. It is only since 2010 that systematic efforts to reestablish the monitoring network have gradually led to the continuation of long-term annual mass-balance monitoring programs (Schöne et al., 2013; Hoelzle et al., 2017). However, detailed subseasonal observations have never been reinitiated. Despite bringing invaluable reference information on the glacier state, the in-situ monitoring remains labor intensive and spatially limited (Zemp et al., 2015). In the absence of direct glacier observations, one of the most common methods to infer annual glacier mass change (Østrem, 1975; Braithwaite, 1984; Kuhn, 1990; Dyurgerov, 1996) or regional glacier mass balance (Kulkarni, 1992; Rabatel et al., 2017) is to use the linear relationship between the remotely observable end-of-summer snowline or snow-covered area fraction (SCAF) and the glacier mass balance. The snowline marks the transition between snow and bare ice surfaces and thus thus approximates the limit between the accumulation and ablation areas of the glacier. The SCAF is the area above the snowline in relation to the total glacier area and therefore represents an altitude-independent proxy for the mass balance (Huss et al., 2013). Dyurgerov (1996) observed the transient snowline as a proxy for the subseasonal mass balance and Pelto (2011) calculated the seasonal snowline rate of change between the available Landsat observations for the Taku glacier, Alaska. The author tied the snowline migration rate to changes in mass balance gradient and concluded that there is a potential for an efficient mass balance assessment from high temporally resolved snowline time series for many years and on many glaciers. Huss et al. (2013) and Barandun et al. (2018) replaced the snowline with the SCAF and its rate of change to calibrate directly a glacier mass balance model.

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Line 46-47, I find it is still hard to understand due to the intrinsic influences of glacier locations and geometry on its SMB dynamics.

This paragraph is restructured in the revised manuscript as part of the restructuring of the Introduction section. The statement is now rephrased as 'altitude-independent'. The SCAF is independent of glacier elevation distribution, whereas the snowline is not. For example, the position of the snowline from different glaciers cannot be compared without considering their altitude distribution. However, the fraction of the area covered by snow can be compared. Furthermore, no elevation information is needed to derive the SCAF, making it easier to calculate it on regional scale. We consider these two points to be advantages that justify the use of the SCAF instead of the snowline.

Introduction: Huss et al. (2013) replaced the snowline with the SCAF and its rate of change to calibrate directly a glacier mass balance model. The SCAF is the area above the snowline in relation to the total glacier area and therefore represents an altitude-independent proxy for the mass balance.

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As for the No.354 Glacier, why did it have the recorded average precipitation lower than the first two glaciers since it experiences frequent summer snowfalls?

Glacier No. 354 is located in the Central Tien Shan, a very dry and cold area. The annual total precipitation is much lower than that at the western margin, where the Abramov and Golubin glaciers are located. This is due to the barrier effect of the westerlies at the orographic margin. The Central Tien Shan is more strongly influenced by the Siberian anticyclone and convective activity in summer rather than by the westerlies. Winters are therefore dry, with most of the snow falling in spring (although this is an order of magnitude lower than at the Abramov and Golubin glaciers). In summer, convective precipitation is more frequent than in the west, and due to the lower temperatures, it mainly falls as snow. However, the amounts of precipitation are still relatively low.

Study sites and data: While main snowfall is recorded in late spring, the glacier experiences frequent small summer snowfall events, which can cover the entire glacier for several days, slowing down the melt (Kronenberg et al., 2016).

Why didn't the authors employ Sentinel-2 data to manually snowline extraction after 2016? Provide more detailed information about the manual extracted snowline.

The S-2 data were used to establish their relationship with the mean NIR from MODIS. Therefore, using S-2 data to validate the produced time series would not be strictly independent, and we used manually derived SCAFs on Landsat images instead. Furthermore, the Landsat images cover also the early study period, enabling validation prior to the Sentinel era and providing an unbiased and independent dataset for validation. We add some more details on the data available and the manual mapping in the revised manuscrip.

Study sites and data To validate our automatic mapping tool, we use SCAFs derived from manually delineated snowlines from independent Landsat imagery from Barandun et al. (2018, 2021) that span between 2000 and 2016 for Abramov, Golubin and Glacier No. 354. These data have been published in Barandun et al. (2015, 2018); Azisov et al. (2022); Kronenberg et al. (2016). We calculate SCAFs for Zulmart in the same way. We download all available Landsat images from 2018 to 2023, then manually map the snow-covered area on ArcGIS and use the RGI outlines to calculate the SCAF for each scene..

When the authors conducted glacier surface classification, how did you treat other possible landcover types (e.g. rocks) as well as shadowed snow? In addition, only the NIR and backscattering information were utilized, I truly doubt if these properties could comprehensively demonstrate the differences between snow and other types of landcover and the availability of the current SCAF S2 and SCAF S1 methods. How did you determine the Otsu thresholds? Have you confirmed the availability of these thresholds in regional applications? The current description is confusing and needs modification. Some published studies which rely on SAR information to discriminate glacier zones (e.g. dry snow, wet snow, percolation and bare ice) have failed to generate a continuous snowline in the Antarctic Peninsula. Moreover, there were significant discrepancies even for same area in same year among different studies due to their various thresholds (please see Zhou et al., 2017, Idalino et al., 2024, Arigony-Neto et al., 2020).

The snow cover has only been mapped on glacier area; other landforms or surface characteristics are excluded. We used state-of-the-art approaches to map snow over glacier ice. Below we try to answer to each point raised in the above comment step by step, highlighting the improvement in the revised manuscript for each topic.

Shadows on snow are an issue in the mapping; that is why we have (i) introduced an adapted method using fixed thresholds when the Otsu method fails and (ii) applied a second-order reclassification depending on the pixel proximity to the snowline. For example, a glacier pixel erroneously classified as ice due to the shadow of rock walls or clouds that lies far above the snowline is reclassified as snow. This procedure is described in L279 in the initially submitted manuscript (Section: Snowline altitude correction). We better explain the threshold method and better highlight the purpose of this correction as follows:

Methods: The main purpose of the classification algorithm is to differentiate between snow-covered and snow-free surfaces. We use the NIR channel reflectance values and apply the Otsu-threshold algorithm (Otsu, 1979) to distinguish snow-covered areas similarly to what is done in Rastner et al. (2019). The Otsu algorithm is designed to find the optimal threshold (th) for each glacier and scene by maximizing the interclass variance between two classes on the image, assuming bimodal distribution on the frequency histogram (here, snow and ice). We have identified three cases in which the Otsu threshold method fails: (i) under completely snow-covered conditions, (ii) when the snowline is above the firn line, and (iii) when cast shadows from clouds are present (Fig. B2). In such cases, the frequency distribution is not clearly bimodal. Thus, an unbound threshold can misrepresent the snow condition over the glacier area. To mitigate this, we defined th_{min} and th_{max} to determine the range of validity for using a threshold determined by the Otsu algorithm. If the initially detected threshold lies outside the predefined th_{min} and th_{max} range, a fixed threshold (th_{fixed}) is applied instead to classify the image. The range $th_{min} < th < th_{max}$ as well as the fixed thresholds are manually identified after comparing classified images with the RGB composites of each glacier to improve classification (Table 3). The same set of thresholds (th_{min}, th_{max}, and th_{fixed}) is applied to the entire time series of preprocessed S-2 imagery per glacier and it is only applied when automatic thresholding fails (thus generally under completely snow-covered or snow-free conditions or cloud shadowing).

Study sites and data: In order to correct for misclassifications such as those due to shadows on snow or unfiltered clouds, we perform SCAF correction for the classified images of S-2 and S-1 in Section 3.1. This is based on the assumption that pixels clearly above the snowline are more likely to be snow covered than snow free and vice versa.

Thank you for pointing out that the methodological section about deriving the transient snowline from SAR backscatter is not quite clear. We expand the respective section to clarify the approach used in the revised manuscript (see below). The used threshold is based on a careful assessment of the images for the four study sites. We are fully aware that this will not be possible in a regional application, which is further explained in the Methods and Discussion sections. Along with that, the challenges presented by S-1 are discussed in more detail in the Discussion section of the revised manuscript.

Methods: C-band SAR backscatter is highly sensitive to the liquid water content in the snowpack. While melt water is usually running off the impermeable glacier ice, melt water percolates and can saturate the snow. In presence of liquid water, the dielectric constant of the snowpack is highly reduced, leading to a higher absorption coefficient in wet snow. As a result, the penetration depth in SAR C band decreases from around 20 m for dry snow to a few centimeters for wet snow, with most of the signal being absorbed or reflected by the upper layers of the snowpack, leading to a substantial decrease in backscatter over wet snow (Nagler and Rott, 2000; Marin et al., 2020; Buchelt et al., 2022). In contrast, dry snow remains nearly transparent to the SAR signal, and the backscatter is dominated by firn and glacial ice below the snow. Its larger grain size and the often high surface roughness of glacial ice lead to increased backscatter values in both cross- and copolarization. This results in pronounced contrasts of the backscatter signal between wet snow and dry snow but also glacial ice, which can thus be used to map the different surface properties. This contrast in the backscatter intensity between wet-snow and snow-free/dry snow-covered surfaces is the basis of the well-established approach in Nagler et al. (2016) to detect wet snow. On a glacier surface, three different surface types can be expected during the melt season along an altitudinal gradient (cf. Zhou et al., 2022): (i) bare-ice zone: low-elevated snow-free areas covered with glacial ice show high backscatter intensity; (ii) wet-snow zone: higher elevated areas (still) covered with melting (wet) snow show low backscatter intensity; (iii) frozen-percolation zone: upper parts of the glacier with completely frozen (dry) snow show high backscatter due to the underlying coarse-grained firn and glacial ice. Consequently, the boundary between (i) bare glacial ice and (ii) melting wet snow on a glacier detected by the difference in SAR backscatter intensity can thus be used as a proxy for the transient snowline (Winsvold et al., 2016). In case of absent wet snow (e.g., during cold spells causing the snowfall of fresh dry snow or refreeze), this approach is not able to accurately detect a transient snowline. Therefore, the approach is limited to the main snow-melt period.

In response to reviewer #1's request, we have also added an example in the Appendixes. Our comparison of SCAFs derived from S-1 also produced favorable results for the glaciers studied during the middle of the melt season. However, the method is clearly limited with regard to dry snowfall at the beginning and end of the season. This is why we conservatively removed all scenes from early and late summer, leaving only a small number of adequate S-1 images. In addition, the overlap with cloud-free MODIS images is limited as those cases were included only when no adequate S-2 acquisition was available. Therefore, the regression relating Sentinel to MODIS meanNIR is not significantly influenced. Based on our findings, we do not recommend using S-1 for further regional-scale applications as long as sufficient S-2 observations are available. Nevertheless, we wish to retain this part of the manuscript in the Discussion section to highlight our methodological findings and the shortcomings of the method.

With respect to the recommended literature on glacier zones in the Arctic Peninsula, we try to relate our approach more clearly with the approach presented in these papers, in particular regarding the different snow elevation zones. Unfortunately, we could not find Arigony-Neto et al. (2020). However, we also want to highlight that literature mentioned in this comment refers to the dry snow zone (DSZ), which is defined as an area that does not melt for a whole year. Due to the different climatic conditions, such areas barely exist in our study region. Besides, information on the DSZ is usually derived from the corresponding winter acquisitions and, therefore, only available on an annual basis, whereas the approach we present in this work requires continuous data throughout the entire melting season.

Study sites and data: We found a threshold of -6 dB to be most suitable, based on the visual inspection of the scenes of the different mountain glaciers.

Discussion: Although S-1 images are not affected by clouds, dry snow is transparent in the C band (Nagler et al., 2016), which excludes accurate capture of summer snowfalls and the end-of-season snowline. Also, a fixed threshold of -6 dB for wet-snow detection is applied here, which is not necessarily optimal for all the study glaciers throughout the ablation season due to the differences in climatic settings, sensor viewing angle, and polarization (Winsvold et al., 2018; Buchelt et al., 2022). Besides, steep terrain could lead to radar layover and shadow effects; however, this issue is limited to very small parts at the study sites. Nevertheless, S-1 can provide valuable snowline observation information independently (see Fig. 4). However, the potential of S-1 imagery is not fully revealed in the present work as this is only used as a backup in case of unavailable or cloud-obscured S-2 acquisitions. In addition, the limitation of S-1 to the main ablation period results in the necessity to always include cloud-free optical images. Thus, the benefit of S-1 is limited for the proposed application as long as enough reliable cloud-free S-2 acquisitions are available.

The Otsu threshold method has been applied in Rastner et al. (2019) on a wide range of glaciers and provided suitable results. The Otsu method automatically performs clustering-based image thresholding on each image individually by assuming that the image contains two classes (snow and ice) and has thus a bimodal histogram. Rock or, in our case, debris on the tongue is usually classified as ice and thus would not affect our classification. More details are provided in Rastner et al. (2019). The optimum threshold for separating the two classes is found when their combined spread is minimal or their interclass variance is maximal. Choosing the correct threshold becomes difficult when the entire glacier is snow covered or the snowline rises above the firn line. To avoid a wrong classification, for such cases a minimum and maximum threshold values are introduced for each glacier based on manual inspection for a range of SCAF between 0% and 100%. If an automatically detected threshold lies outside this range and thus no optimal threshold can be found, a fixed threshold is assigned. This fixed value is also manually selected. We include an example (Fig. B2) and the results from a sensitivity analysis in the Annexes of the paper and clarify the threshold choice in the Methods section.

Study sites and data: The main purpose of the classification algorithm is to differentiate between snow-covered and snow-free surfaces. We use the NIR channel reflectance values and apply the Otsu-threshold algorithm (Otsu, 1979) to distinguish snow-covered areas similarly to what is done in Rastner et al. (2019). The Otsu algorithm is designed to find the optimal threshold (th) for each glacier and scene by maximizing the interclass variance between two classes on the image, assuming bimodal distribution on the frequency histogram (here, snow and ice). We have identified three cases in which the Otsu threshold method fails: (i) under completely snow-covered conditions, (ii) when the snowline is above the firn line, and (iii) when cast shadows from clouds are present (Fig. B2). In such cases, the frequency distribution is not clearly bimodal. Thus, an unbound threshold can misrepresent the snow condition over the glacier area. To mitigate this, we defined th_{min} and th_{max} to determine the range of validity for using a threshold determined by the Otsu algorithm. If the initially detected threshold lies outside the predefined th_{min} and th_{max} range, a fixed threshold (th_{fixed}) is applied instead to classify the image. The range $th_{min} < th < th_{max}$ as well as the fixed thresholds are manually identified after comparing classified images with the RGB composites of each glacier to improve classification (Table 3). The same set of thresholds (th_{min}, th_{max}, and th_{fixed}) is applied to the entire time series of preprocessed S-2 imagery per glacier and it is only applied when automatic thresholding fails (thus generally under completely snow-covered or snow-free conditions or cloud shadowing).

In our opinion, the validation with SCAFs derived from manually delineated snowlines shows satisfactory results, and we therefore believe that, overall, the state-of-the-art methods used in our study perform adequately to classify snow on glaciers.

How did the authors treat the different spatial resolution when you merge SCAF S1 and S2 results?

We did not merge a spatially distributed SCAF but only a SCAF value. Thus the resolution difference was not an issue. We gave preference to S-2 images when we had two scenes from the same date.

I don't think there is a nice consistency between MODIS-based SCAF and manual results before the joint employment of S1 and S2 in Figure 4. If possible, please provide some quantitative analysis.

We provide RMSE between the Landsat observations and the MODIS-based SCAFs in Figure 5. Unfortunately, only little data is available before 2016, and the overlap of MODIS-based SCAF and Landsat is sparse for a sound quantitative analysis of shorter periods.

Line 338, why is this large difference? As for Glacier No.354, the SCAF S1 is close to 0 while that from MODIS-based SCAF is higher than 0.75, which one could represent real conditions? Since there exhibits such significant discrepancies even in 2018, how confident the authors are when fetching SCAF by utilizing the regression functions?

We thank the reviewer for pointing this out. In Fig. 4 of the manuscript, the S-1 classified SCAF towards the end of the season is shown, and we want to highlight issues related to dry snowfall events at the beginning and end of the season. These images were excluded when producing the regression model—as described in the manuscript (L296), images from after mid-August were excluded. The Fig. 4 clearly shows that, at the end of summer, fresh snowfall (often on Glacier No. 354; e.g., 2018) is not detected by S-1 but is observed by optical sensors. Consequently, the S-1 classification indicates a completely snow-free glacier, whereas, as visually confirmed by the late author, it is in fact snow covered. We are therefore confident that our method and the classification of the optical S-2 images correctly represent such conditions. Once again, we would like to highlight the limitations regarding S-1 and dry snow. We attempt to formulate this clearer in the revised manuscript.

Figure 4: Glacier SCAF evolution during the melt season derived from MODIS-based SCAF, Sentinel-1, Sentinel-2, and manually from Landsat imagery for 2008 and 2018. Sentinel-1 (only images prior to mid August) and Sentinel-2 images from 2016 to 2023 are used to calculate the regression model to derive the MODIS-based SCAF from 2000 to 2023. Manually derived SCAFs from Landsat provide an independent validation of the regression model. Sentinel-1 and 2 perform well when snow is depleting; however, Sentinel-1 fails to appropriately map fresh snow fall (dry and fine layer of snow, e.g., for Glacier No. 354 at the end of the ablation season).

Methods: Figure 4 shows a clear example of the disparity between S-1 and MODIS-based SCAFs towards the end of the season for Glacier No. 354 in 2018. This illustrates how S-1 cannot capture fresh snowfall, which is more frequent at the end of the ablation season, and consequently the detected SCAFs remain erroneously low for S-1. In contrast, SCAFs detected by the optical S-2 sensors indicate a snow-covered glacier (visually validated) that agrees with the MODIS-based SCAFs.

Line 374, I don't see any trend to a later end of the melt season has become visible since 2009.

This statement is now removed from the revised manuscript.

Line 379, what do you mean that snowline rate changed by -1.25%/day? Could you illustrate this by utilizing meters for SLA dynamics? I don't think it is appropriate to directly treat snowline as SCAF.

We apologize for the confusion between snowline and SCAF. This issue is solved in the revised manuscript, and we now use the rate of change of the SCAF (%) (here and everywhere throughout the manuscript).

Results: We found the annual SCAF rate of change for 24 years to fluctuate between -0.2 and -1.25%/day for all the study glaciers, except for Glacier No. 354, as there the SCAF depleted faster reaching -2%/day in 2014 (Fig. 8).

It is better to provide a figure with SLA information overlapping with remote sensing images to directly exhibit the identification accuracy.

As the MODIS-based SCAF is not a spatially distributed product, such a comparison is not possible.

Figure 3 to Figure 6, all these figures can be improved.

We haver worked on figures 3 to 6 to improve their readability, also taking into account the comments from reviewer # 1.

2.3 Specific Comments

Line 11, Give some quantitative descriptions about the earlier exposure of bare ice.

The Abstract is now reformulated in the revised manuscript. Please refer to our answer to the general comments above.

Line 13, Considering your research period began from 2000, and some glaciers have already exhibited accelerated snow depletion rates. I wonder how you selected these four glaciers. Is it a bit deliberate?

We are afraid we were not able to grasp the sense of the term 'deliberate' in this comment. The glaciers where chosen responding to the need to cover the different climatic settings in the Tien Shan and Pamir and because they are part of the glacier monitoring program in Central Asia, which means having mass balance data available. Since, for every glacier, the relationship between the SCAF from S1/S2 and the maanNIR from MODIS must be established individually, it is not relevant which glaciers are selected. The purpose of choosing well-studied glaciers for method development is to have data available for validation and proof of concept. The following paragraph is added in the revised manuscript to clarify the motivation behind the study site selection:

Study sites and data: All glaciers are subject to the regional glacier monitoring program, which provides extensive data for validation. They are thus ideal sites for developing and testing the proposed methodology.

The following comments are corrected accordingly in the revised manuscript. We apologize once again for the errors in cross-referencing and the missing citations:

- Line 19: Modify to 'by the World Meteorological Organization (WMO) in 2022'.
- Line 22: Add references.
- Line 35-40: Please add some newly published literature.
- Line 60: missing references.
- Line 83: missing '.'.
- Line 105: missing '.'. There are too many similar problems in the whole manuscript.
- Table 1: It should be 'in-situ', and as for locations, missing the specific °N and °E.
- Figure 1: missing '.' in the last sentence. Too many similar errors in the manuscript and I won't list each one of them.
- Line 107: (?). What do the authors mean?
- Line 161: Remove 'great'.
- Lines 166 and 171: Add corresponding references.
- 2.2.2 Radar Data
- Line 176: Add corresponding references.
- Line 233: Why used the Italic style?
- Line 250: It should be 'similar as in Rastner et al., (2019).'.
- Line 256: '(3)' ?
- Line 330: Where is Fig. 4.1.2??

The following comments are clarified or specified in the new submitted manuscript:

- Line 57: As for reflectance, give some specific ranges.
- Line 66: Which albedo product? Be more specific.
- Line 70: How long?
- Line 75: Give specific number of the coarse resolution.
- Line 84: Which new satellites?
- Line 243: 'land images'?
- Line 290: Why '20%'?
- Line 91: Correct the misrepresentation. Moreover, 'improve sub-seasonal mass balances and glacier melt water contribution'?
- Line 111: How could it be possible that a 1996 paper includes the data during same period as temperature data collected until 1998?
- Line 306: Why 1.5 SD?
- Figure 3: Add the corresponding function in each sub-figure.
- Line 316: Why choose 2000-2023 and 2009-2023? Needs demonstration.
- Line 461-462: hat do you mean?

———

Line 80, add a brief explanation on the low backscattering of melting snow.

This is changed accordingly in the revised manuscript

Introduction: As the snow starts to melt, the dielectric constant of the snowpack is highly reduced, leading to a higher absorption coefficient in wet snow. Thereby, most of the signal is absorbed or reflected by the upper layers of the snowpack, resulting in a much lower backscattering than bare ice, which allows to map wet snow on glaciers (Rott and Mätzler, 1987).

———

Line 276, how did you find the -6 dB is suitable? Need more explanation.

Please refer to our answer to the general comments above. We found the best performance for the selected sites using -6 dB.

———

Line 295, Sentinel-1 data failed to detect dry snow? See Zhou et al., 2017, Idalino et al., 2024, Arigony-Neto et al., 2020.

Thank you for pointing out that this statement might be misleading. However, as already discussed for another comment above, the literature mentioned in this comment refers to the dry snow zone (DSZ), which is defined as an area that does not melt for a whole year. Due to the different climatic conditions, such areas barely exist in this study region. Besides, information on the DSZ is usually derived from the corresponding winter acquisitions and, therefore, only available on an annual basis, whereas the approach we present in this work requires continuous data throughout the entire melting season. Even so, to clarify this statement and avoid a potential misleading meaning, we adjusted the sentence as follows:

Methods: As our approach using S-1 only works reliably if a wet-snow zone is detectable (see Sec. 3.1.4), end-of-season SCAF had to be removed after mid-August for each year.

———

Line 345, is it a satisfactory accuracy for an RMSE lower than 20%?

Given the nature of the input data, we consider the method to be reliable within the expected uncertainty. The issue of many areas remaining ambiguous is present even when mapping snow-covered areas manually on satellite images, and the process still relies heavily on expert knowledge. Such areas include slush, superimposed ice, and refreezing crusts, to name a few. An additional complication arises when the snowline rises above the firn line. Uncertainties in mapping are higher for lower SCAFs. In Barandun et al. (2018), an experiment was conducted to classify manually the minimum and maximum possible snowlines, depending on whether ambiguous areas were classified as snow or ice. The differences were particularly significant around the median elevation of the glacier. The same study estimated the uncertainty of automatic mapping of Landsat images to be 8–13% compared with manual mapping. This result is slightly better than our findings, which is not surprising given the higher resolution of the Landsat images used for mapping compared with that of the MODIS-derived SCAF used in the present work. The paragraph appears now in the revised manuscript as follows::

Methods: We compared the SCAFs derived from $glacierSCAF_{MODIS}$ with the SCAFs manually derived from Landsat (Fig. 5). Abramov glacier, Glacier No. 354, and Golubin glacier exhibited an RMSE below 20%. For these three glaciers, the $glacierSCAF_{MODIS}$ results are systematically underestimated by an average of 16%. Visual inspection of the corresponding Landsat scenes indicates that the variation is greatest within the 50–65%

SCAF range. This range is close to the median elevation of the glacier, and in the case of the three glaciers, it is an area prone to ambiguous surface types, such as slush, superimposed ice, and refreezing crust formation. SCAFs at around 30% are close to the firn line. When the snowline rises above the firn line, the distinction between firn and snow becomes extremely difficult, even for manual mapping. Zulmart glacier shows slightly less good agreement, with an RMSE of 25%. SCAFs in the lower ranges (0–50%) are overestimated by an average of 19.7% on MODIS images. Superimposed ice and refreezing are frequent on Zulmart glacier. It is very difficult to correctly map bright refrozen meltwater, even with manual mapping.

Line 391, more negative? Give quantitative description.

We were unable to link this comment to the given line number. We must apologize for, consequently, not taking it into consideration.

Line 439-445, this paragraph has to be re-organized.

The paragraph is now reorganized in the revised manuscript as follows:

Discussion: Our findings suggest that similar annual surface mass balances can result in very different SCAF seasonal distributions. To accurately predict meltwater, this discrepancy must be considered, especially given the expected future changes in seasonal meltwater contributions during the dry summer months (Huss and Hock, 2018; Armstrong et al., 2019). Below we detail the key findings for each of the four remote glaciers analyzed in the present work and discuss their implication on meltwater contribution to the total river runoff. By combining more than 20 years of almost daily SCAF observations with modeled subseasonal mass balance time series, we are able to link the key changes in close-to-daily glacier SCAF dynamics with subseasonal monthly meltwater contribution changes for glaciers located in the two major rivers basins of Central Asia: the Syr Darya basin (Golubin, Glacier No. 354) and the Amu Darya basin (Abramov).

5.2.2 Uncertainties and limitations, this part also needs to be re-organized.

The paragraph is now reorganized in the revised manuscript as follows:

Discussion: $glacierSCAF_{MODIS}$ performance depends primarily on the quality of the MODIS cloud mask and on the accuracy of the mapped snowlines obtained from S-1 and S-2. This method is based on the regression between the mean NIR reflectance extracted from MODIS and the SCAF obtained from S-1 and S-2. We found the decay exponential function (increasing form) to be the best suited one to approximate the relationship between the Sentinel derived SCAF and the mean NIR MODIS value (Fig. 3). As expected, the lower MODIS-based SCAF values are more sensitive to small changes in mean NIR reflectance, and the end-of-season values below 20% are subject to higher uncertainties than the SCAF values during the season. For persistently cloud covered glaciers, such as Glacier No. 354, a blurred end-of-season snowline is obtained as a result of a less frequent observation combined with the low reliability of the cloud mask. Under such conditions, the snowline dynamics of the glacier are more challenging to resolve.

Line 545-547, this sentence seems unreasonable to me, could the optical based method hamper the utilization of SAR data?

Here, we use Sentinel data to establish a relationship with the MODIS mean NIR, rather than using them directly as input for SCAF time series. Therefore, we only rely on scenes that overlap between Sentinel and MODIS. The advantage of S-1, which is unaffected by clouds, is therefore limited, since we cannot have corresponding MODIS images—which are sensitive to clouds and therefore discarded. This is what we mean in the statement at line 545 ff. We try to further clarify this question in the revised manuscript.

Discussion:Although S-1 images are not affected by clouds, dry snow is transparent in the C band (Nagler et al., 2016), which excludes accurate capture of summer snowfalls and the end-of-season snowline. Also, a fixed threshold of -6 dB for wet-snow detection is applied here, which is not necessarily optimal for all the study glaciers throughout the ablation season due to the differences in climatic settings, sensor viewing angle, and polarization (Winsvold et al., 2018; Buchelt et al., 2022). Besides, steep terrain could lead to radar layover and shadow effects; however, this issue is limited to very small parts at the study sites. Nevertheless, S-1 can provide valuable snowline observation information independently (see Fig. 4). However, the potential of S-1 imagery is not fully revealed in the present work as this is only used as a backup in case of unavailable or cloud-obscured S-2 acquisitions. In addition, the limitation of S-1 to the main ablation period results in the necessity to always include cloud-free optical images. Thus, the benefit of S-1 is limited for the proposed application as long as enough reliable cloud-free S-2 acquisitions are available.

Line 593, could merely four glaciers represent the glacier conditions in the wide Pamir and Tien Shan regions?

We agree with the reviewer and the statement is changed in the revised manuscript.

Discussion: We found that the two Tien Shan glaciers investigated here exhibit increasingly heterogeneous SCAF dynamics in terms of both timing and magnitude. In contrast, the two Pamir glaciers studied have responded more uniformly in recent years.

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