Answers to Referee #2

In the following, the comments from the reviewer are in shown in black and our answers are in **bold blue**. References from the manuscript are shown in *italic*. The changes applied to the manuscript (revised version) are *underlined*. The line numbers refer to the original preprint.

I enjoyed reading this paper, and to my understanding this approach of mapping rock glaciers based on a given set of assumptions and definitions seem to be well founded and carried out in a thought through manner. I find the considerations accounted for in the manuscript to be meaningful and interesting, and the paper seems like a natural next step following the work carried out by the RGIK group. There are a few things I think could improve the manuscript a bit, and this would mainly be for readability and overview.

Thanks a lot for the positive feedback and the valuable comments to improve the manuscript.

Section 2.1: you describe a bit how the exercise was performed, but could you perhaps elaborate a bit here? For instance, were mapping teams assembled randomly, or did they comprise individuals with local expertise? Table 1 suggests that the principal investigator of each team possesses some or significant area-specific knowledge, but what about other team members? From my own background I know that it can be quite difficult to 1. change my opinion about familiar terrain, and 2. communicate my interpretation of landforms to local experts in areas that I lack familiarity with. I assume that you found ways to handle this, but it would be nice to know.

Thanks for the comment. A sentence mentioned (partly) this point in section 2.2 (l.100-102), but this was somewhat misplaced. We moved it to section 2.1 and added new information about the way the teams have been assembled:

A Principal Investigator (PI) was designated to coordinate the work of the inventory team in each area. All PIs had past or ongoing research in the area they were leading. The volunteer operators were found within the involved institutions and after a call for participation in June 2023 using the RGIK mailing list (about 200 subscribers). The participants were free to choose in one or more area(s) to perform the work, depending on their interest and time availability. To ensure enough operators in each area, as well as a diversity of geographical background, competence and seniority, members of the PI team acted as operators in areas where few people signed up. The resulting inventory teams were composed of five to ten operators (including the PI; Table 1). Some operators worked in several areas. One operator (R. Delaloye) performed the work in all the areas, which helped communicating common challenges and coordinating key decisions across the teams. The exercise involved a total of 41 persons (see Author list and Acknowledgments).

In **table 1** you include the numbers of RGUs within each area, this is really a result. Instead, consider including information on the materials available in each study area, such as orthophotos (with resolution), DEMs (with resolution), and InSAR quality and availability. This extra information might fit better in chapter 3 after you go through the content of the input data.

Thanks for the comment, which overlaps with a similar suggestion from reviewer 1. We have added a new table 2 for input data (see below). We removed the number of certain RGU in table 1, and replaced it by information about the elevation range in the AOI.

Table 2 (placed before Figure 3, in section 3.1):

Summary of input data in each RoGI area. The names and locations corresponding to the area numbers are shown in Table 1. The crosses (x) highlight the availability of the corresponding dataset. For InSAR data: the yy-yy numbers correspond to the years available for each InSAR dataset (e.g., 15-19: interferograms or averaged velocity maps between 2015 and 2019).

Area number	**5-1**	**6-1**	**7-1**	**8-1**	**9-1**	**10-1**	**11-1**	**12-1**	**13-1**	**14-1**	**15-1**	**16-1**
Satellite Web Map Services (WMS): Optical imagery and topographical map												
Google satellite WMS	x	x	x	x	x	x	x	x	x	x	x	x
Bing satellite WMS	x	x	x	x	x	x	x	x	x	x	x	x
ESRI satellite WMS	x	x	x	x	x	x	x	x	x	x	x	x
OpenTopoMap WMS	x	x	x	x	x	x	x	x	x	x	x	x
Additional optical/thematic data: HR aerial imagery and national topographical map												
Extra HR aerial image	x	x	x	x	x	x						
National topo. map		x	x	x		x						x
DEM products: Low/High-Resolution (LR/HR) DEM and/or associated products (e.g., hillshades, slope, aspect)												
LR DEM (10–30m)	x	x	x	x	x	x	x	x	x	x	x	x
HR DEM (< 10m)	x	x				x	x					
InSAR data: Wrapped interferograms (ifgs) and velocity maps from Stacking and Persistent Scatterer Interferometry (PSI)												
Sentinel-1 ifgs	16-19	17-19	17-19	17-20	18-20	16-19	18-19	15-19	15-19	16-19	18-20	15-23
ERS-1/2 ifgs									98-99	91-95		
ALOS-1 ifgs						07-10	07-10		06-10	06-09	08-11	07-08
ALOS-2 ifgs	14-19	14-21						15-17	14-16	15-16	16-19	
SAOCOM ifgs		21									21-22	21-23
Cosmo-SkyMed ifgs							16-20					
TerraSAR-X ifgs		09-14										
6–12d ifgs Stacking		19	15-19	15-20	15-20	18-19	18-19	18	18	18-19	18-19	18
Combined 6d–annual ifgs Stacking			15-19	15-20	15-20							
PSI	15-21			15-19								

Figure 3: The text and symbols are quite small, making it difficult to read.

Thanks for the comment. We made a new version, which is hopefully easier to read:

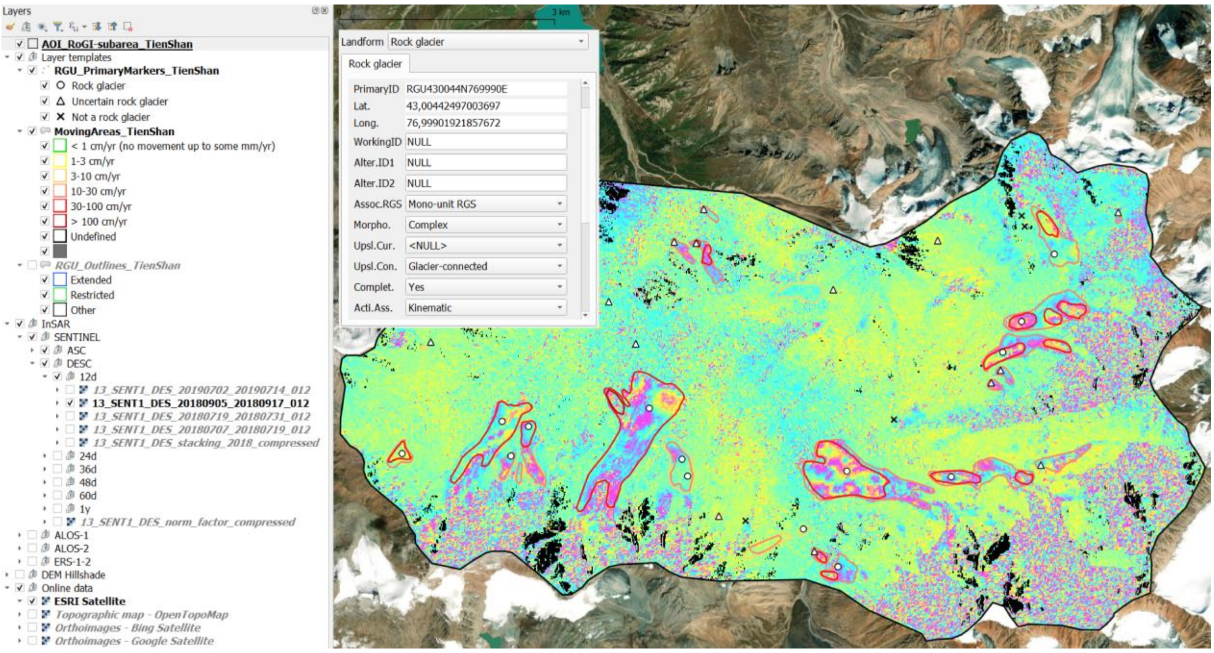

Figure 3. *Example of QGIS data structure and dialog box for semi-automatic attribute filling in area 13-1 (Northern Tien Shan, Kazakhstan). An example of Sentinel-1 wrapped interferogram is displayed within the AOI extent. The boundaries of the RoGI area (black polygon), the PM (white dots and triangles), and the MA (yellow to red polygons) are displayed as top layers. For sake of*

visualisation, the GO layer is not shown. See example with GO in Figure 4. Background map: ESRI Satellite Web Map Service.

Figure 4: The legend contains an entry for "not a rock glacier," which is not previously mentioned in the manuscript. It is acknowledged in Section 5.1 as potentially misinterpreted landforms, serving as an educational element. However, it may be more appropriate to exclude this annotation from the figures. Instead, incorporating it into attribute tables or supplementary materials like you have done could facilitate learning, so it might be useful to keep.

Agree. Removed in this figure. The details/explanations about why a landform is categorised as "not a rock glacier" are included in the PM attribute tables. In addition, we noticed that the current figure did not include the PM of all operators (black dots/triangles), which was an error. This has been corrected.

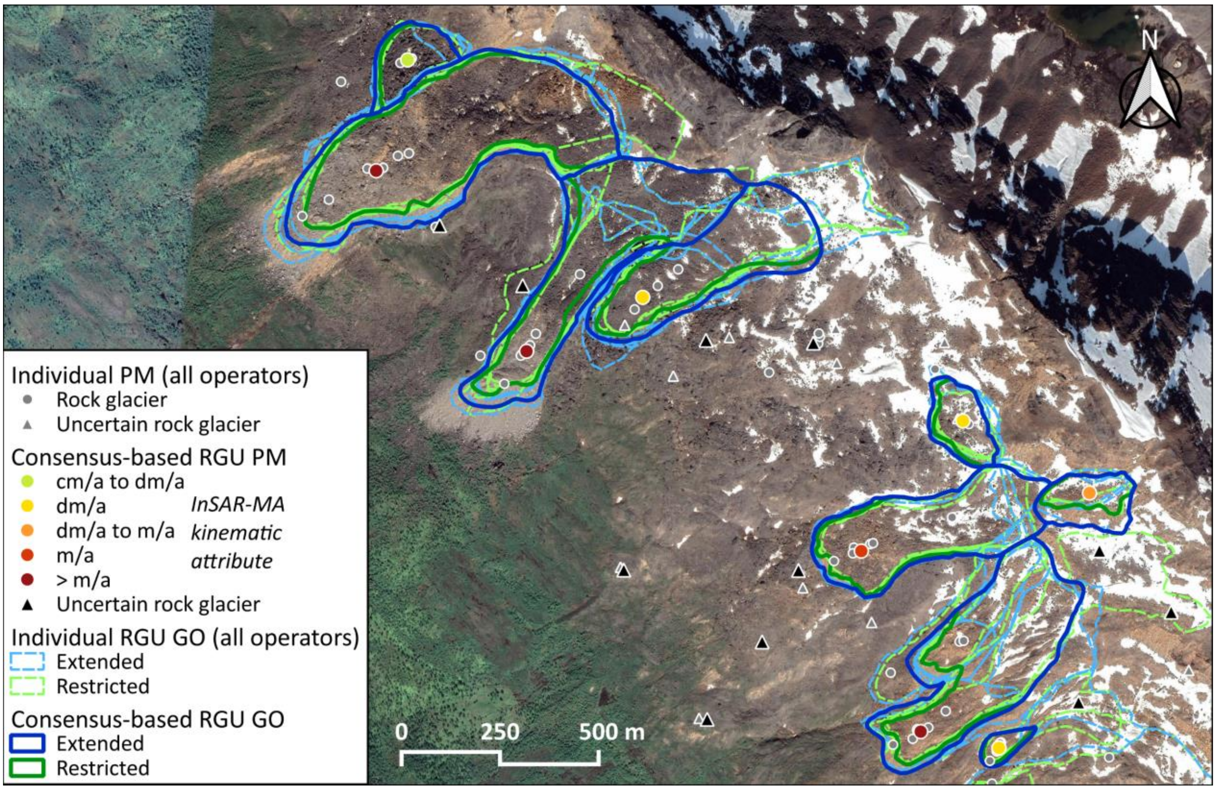

__Figure 4.__ Example of RoGI results in part of area 7-1 NO-T (Troms, Norway), showing individual operator results and final consensus-based results (Primary Markers: PM; Geomorphological Outlines: GO). For sake of visualisation, the MA layer is not shown, but was used to assign the PM kinematic attribute displayed here with a green–red colour scale. See example with MA in Figure 3. Background: NorgeiBilde orthophoto (2016-08-2016).

Chapter 4: Consider restructuring this chapter to begin with the description of study areas (Section 4.1 onward) before presenting Figures 5-8. This change could enhance the comprehension and interpretation of the figures.

Agree. We changed the structure as suggested, adding a section 4.13 (Results summary across all areas), after the description of each area (sections 4.1-4.12). We added the following sentence in the introduction of Section 4 (l.287): "*In the following, we describe the results in each area separately (Sections 4.1–4.12) before summarising the findings across all areas (Section 4.13)."*

I appreciate how challenges and uncertainties across regions and operators are summarized, reflecting the inherent difficulties in interpreting geomorphology in certain areas. I also like that you address some issues connected to how we traditionally have interpreted intact landforms as active, while in the kinematical and more recent definitions these are considered transitional or even relict. Maybe such observations could challenge the value we add to the current movement rates in high-arctic areas.

In general, I especially enjoyed reading the quality assessments of the different products mapped, i.e. the results of this exercise. I think you go through the different points carefully and thoroughly, and I gained some new insights while reading.

Thanks a lot for this positive feedback, much appreciated!

Map material:

To me this looks good, and with some help from the descriptions in the appendices it was quite easy to navigate in the mapped material.

From the text, I cannot read whether you did some "user sensitivity" tests or what to call it. It appears there are notable differences between the extended and restricted rock glacier outlines between some regions. Were systematic, regional differences in extended and restricted RG areas assessed? You mention this a bit in sec. 5.2.1. and 5.2.3., and maybe this issue is mainly addressed in the attribute tables as low outline reliability. However, when I had a look at one of the rock glacier outlines (RGU707506N277873E) in Finnmark where there is a rather large difference between the restricted and the extended outline of the front, the extended front position is marked with 2 (high reliability) while the restricted front position is marked with 1 (medium reliability), while both have 0 (low reliability) connected to their upslope margins. The uncertainties of the upslope margins are well accounted for in the text, but from the mapped material to me it looks like it is the front positions that are uncertain in this specific case. I had a look at the other rock glaciers in the same area, and the ones I had a look at seem to be classified in the same way. (I only looked into a few in the vicinity of RGU707506N277873E.)

We have not performed a systematic inter-regional sensitivity analysis of the GO outlining process. Despite the despite the effort to standardise the procedure and reduce the differences between the regions, we acknowledge that some discrepancies remain. These are due to the different (and partly subjective) choices of the teams but also to real geomorphological differences between the areas. In accordance with a similar comment from reviewer 1, we modified the start of section 5.2:

Here we summari<u>s</u>e the observations about the <u>uncertainties and limitations</u> of the three output files, based on the results in the 12 areas and the feedback of the operator teams. <u>Most challenges are common for all areas, while a few are affecting specific areas only. The main identified uncertainties and limitations of each output product are described in the following sections and summarised in Table 3. Despite the effort to standardise the procedure and reduce the differences between the areas, we acknowledge that discrepancies remain in the final products. These are due to the different levels of geomorphological complexity, the variable numbers of landforms and the density of their distribution, as well as the heterogenous data quality, local knowledge and research history. In case of operator discrepancies, the decisions were taken at the team level, ensuring homogeneity within each area. Major questions were discussed PI coordination meetings and communicated across the teams thanks to operators working in several areas. The parallel timeline of the work in all areas contributed to a good</u>

communication on the common challenges, but did not discard all risks of inter-regional differences and subjective treatment.

We had partly mentioned the question of the uncertainty of the front delineation in the second bullet point of 5.2.3, but agree it was less discussed compared to the upper boundary. The case you described in Finmark is a landform with a quite smoothed front, for which the location of the restricted outline is ambiguous, due to rounded topography. We have made the following modification in 5.2.3 to include this point:

In some cases, the delineation of the front was challenging, especially if the toe of the rock glacier was reworked by other processes, such as solifluction. Smooth fronts and rounded ridges and furrows, often associated with relict and transitional landforms, may lead to ambiguous delineation of the restricted outlines. For a rock glacier developing on a steep slope, the front may also be difficult to distinguish. Some problems were for instance identified in cases of exaggerated fronts blended with the downside talus slope. Small rock glaciers, such as debris-mantled-connected rock glaciers, or embryonic talus-connected landforms (protalus ramparts) often had ambiguous lateral margins, challenging for outlining. Such complicated cases were discussed during team meetings to find a mutually agreeable solution. When the location of the boundary was uncertain, the front and/or lateral outline reliability was set to "low" or "medium" in the attribute table.

Additionally, I am a bit confused by the discrepancies between rock glacier outlines and MA polygons. Could you clarify why these sometimes overlap and other times do not? While only "certain" rock glaciers are outlined, many polygons with MA values are neither marked as "uncertain" nor as "not a rock glacier" in the mapped material. Conversely, there are instances where RG outlines exist without corresponding MA polygons (e.g. Disko, Greenland).

The moving area detection/delineation is based InSAR only. The polygons are not necessarily following the landform margins. It only shows where movement has been detected. If the movement is heterogenous and/or if InSAR is affected by limitations (data gap, underestimation due to slope orientation diverging from the radar viewing angle, decorrelation due to snow, etc.), the MA polygon may only be partly overlapping with the rock glacier.

The MA step is performed in parallel to the PM step. Partly iteratively (cause InSAR may help to detect new landforms) but partly independently considering that the MA outlines were delineated before the team decision on the final PM selection. It means that when it was a doubt at this stage (rock glacier, not a rock glacier, uncertain?), the operators may have decided to draw a MA. If the associated landform was discarded after the team discussion (not a rock glacier or uncertain), the MA remained (information of movement but not associated to a certain rock glacier). We believed it would have been a waste to remove the information, even if some MA are not related to a rock glacier but something else, e.g. solifluction or landslide. That could be of interest as well! In Finnmark, for instance, we comprehensively mapped the movement within the entire area considering the complex interaction of several periglacial processes. We kept this information although several MAs were not further used in the next steps of the exercise.

Your question showed the need to add more explanations on the way InSAR has been used. We therefore extended the description of the MA step, in section 2.2:

Detect, delineate, and classify Moving Areas (MA) using InSAR. *This task was performed in parallel, potentially iteratively, with the first bullet point (RGU identification with PM). The MA were identified, delineated, and characterised based on InSAR data (see Section 3.1). For each area, the operators used a similar collection of radar image pairs (interferograms) from different spaceborne radar sensors, with different viewing geometries and variable time intervals between the image acquisitions. In some areas, multi-temporal InSAR mean velocity maps based on Distributed Scatterer (DS) and Persistent Scatterer (PS) algorithms were also available (Table 2). Each recognised MA was delineated in a dedicated polygon vector layer. The attributes documenting the velocity class, the observation time window and validity time frame, and the MA reliability could be filled using a semi-automatic dialog box. The attribute table of the MA layer is shown in Appendix B. The boundaries of the MA polygons follow the InSAR signal, not the landform features. If the movement is heterogenous and/or if InSAR is affected by limitations, the MA may only be partly overlapping with the rock glacier. The MA step was performed before the team decisions on the RGU final locations, which means that some delineated MA may correspond to surface movement associated to uncertain rock glaciers or other periglacial processes. Such polygons were kept in the final layer but were not further used for morpho-kinematic characterisation when they did not correspond to a certain RGU. If no movement was detected on InSAR, no polygon was drawn. Several rock glaciers have therefore no corresponding MA. The complete procedure is explained in the RGIK practical InSAR guidelines (RGIK, 2023b).*

The case of a rock glacier without any MA is more usual, cause the presence of a rock glacier is not necessarily associated with a detected movement. The absence of detected MA can be either due to 1) no movement (or too low to be detected), or 2) low data quality and/or coverage which did not allow for detecting it. If we can ensure that the absence of movement is caused by 1) a KA category < cm/yr can be assigned and the activity attribute is set to relict based on this information. If we do not know (low or uncertain data quality/coverage), the activity assessment relies on a geomorphological analysis. Such decision is not straightforward and has been identified as a challenge that we need to clarify in the guidelines. See third bullet point in 5.3.2:

The assignment of the activity attribute based on geomorphological and/or kinematic criteria requires clarification in the guidelines. The InSAR analysis led to the generation of a MA layer with polygons highlighting where movement has been detected. For characterising the kinematics and the activity, the operators used the MA layer as input. However, some rock glaciers are not covered by any MA. In such cases, it was recommended to avoid overinterpreting the absence of detected movement, because a rock glacier without any MA may mean two different things: 1) there is no movement or too low to be detected, 2) the data quality and/or coverage did not allow for detecting it. In such cases, some operators only focused on geomorphological criteria to assign the activity. A kinematic attribute with low velocity and low reliability index may have been documented, but was not used to set the activity. For other operators, the lack of movement evidence has been used in synergy with geomorphological evidence, as an additional indicator confirming the geomorphological interpretation.