Reply to comments by G. Liu on “Mapping and inventorying active rock glaciers in the Northern Tien Shan (China) using satellite SAR interferometry”

General comments

After more than two decades silence, this manuscript offers us new knowledge, evidences and research methods about rock glaciers and permafrost distribution in the Northern Tien Shan of China. The paper based on 261 active rock glaciers which were recognized by combines SAR interferometry and optical images from Google Earth, give a detail discussing of their locations, geomorphic parameters, and down-slope velocities, and marking permafrost lower limit. This research is reference significance for alpine Periglacial landform research and permafrost mapping in the remote regions.

We thank Prof. G. Liu for his positive comments on our approach and results. We also appreciate his careful consideration and detailed comments. Our replies are highlighted in blue.

Specific comments

(1) Recognition of rock glaciers:

- According to the manuscript and the supplement, most of the 261 active rock glaciers were correctly identified, yet some misreading appeared, for example, ARG 70, ARG 131 should be MARG.

Authors: Thanks for your correction. We have accordingly corrected the types of ARG70 and ARG131 as MARGs. We also revised the relevant statistics related to the MARGs and TARGs through the paper.

- By the limitation of satellite data and research technique, a large number of small rock glaciers are not identified and compiled, especially the talus derived. For example, rock glaciers in the head water of Urumqi River reported by Cui and Zhu (1989), Zhu (1992), Zhu et al (1992), Liu et al (1995), not mentioned by the authors.

Authors: It is true that we may have missed some small rock glaciers because the InSAR phase maps have a moderate spatial resolution of 15 m. We have highlighted this potential limitation of our method in Section 4 (see Lines 259–268).

Following the reviewer’s suggestion, we have added a discussion subsection to compare our inventory with the previous studies on rock glaciers in the Tien Shan (Cui and Zhu, 1989; Gorbunov et al. 1992; Zhu 1992; Zhu et al.1992; Liu et al. 1995). We have reviewed and compared the altitude distribution, geomorphic descriptions and surface velocities of the rock glaciers that have been documented in these studies with our results (see Lines 409–435). However, we can only perform a qualitative, not quantitative, comparison. This is because (1) the exact locations of the rock glaciers documented in these studies are not available; (2) the method we adopted to map active rock glaciers is significantly different from the method used in these previous studies, making the comparison impractical.

- ARG 94 was recognized as TARG, in the same way, site a (43.6429◦N, 85.4292◦E ;) and b (43.6380◦N, 85.4284◦E) should be TARG. This greatly reduces the accuracy of number, regional and altitude distribution of the rock glaciers. This therefore, affect use of active rock glacier to determine permafrost lower limit.

Authors: We have investigated the two locations of site 'a' (43.6429°N, 85.4292°E) and 'b' (43.6380°N, 85.4284°E) on the Google Earth images. From the geomorphic features, we interpret that these two sites host two talus-derived rock glaciers. However, we found that our InSAR phase map suffers from severe de-correlation problem at these two locations, likely due to radar shadows. Therefore, we excluded them from our inventory. We have pointed out that the number of ARGs we compiled is a conservative estimation of all the ARGs in the NTS, and listed several reasons for this kind of conservative estimation (please see Lines 259–268). This is also why we gave a range of estimations rather than exact values of the lower altitude limits of permafrost, as described and justified in Section 4.4. Nevertheless, as discussed in Section 5.3, the distribution of the ARGs we inventoried are in good agreement with these three existing permafrost maps in the Northern Tien Shan.

(2) Identification of the initial line point (ILP) and front line point (FLP):

- It is not very clear how to determine ILP for talus derived rock glacier, for example ARG22, 51; and moraine derived rock glacier, for example ARG 50, view Google Earth, the ILP located at moraine covered glacier.

Authors: As described in the first paragraph in Section 3.3 (Lines 220–230), we determined the initial line point (ILP) and front line point (FLP) of a rock glacier based on both the InSAR phase measurements and the geomorphological features from the Google Earth images. The variations of the InSAR phase represent ground movements, and thus we can outline an active rock glacier (ARG) based on the InSAR phase variations. We interpreted the active boundary in the rooting zone of an ARG as the initial line where the permafrost starts to creep. We then used the central point of the initial line as the ILP. The FLP of the ARG can be determined based on the similar method. In addition, the FLP is generally located in the lowest place where a rock glacier can reach, which can be easily identified from the Google Earth images. For example, Fig. R1(a) below shows the outline of the ARG22 determined from the InSAR phase variations. Fig. R1(b) shows the corresponding

Google Earth image. We have rewritten the relevant text in Section 3.3 to clarify our method for identifying the ILP and FLP (see Lines 220–230).

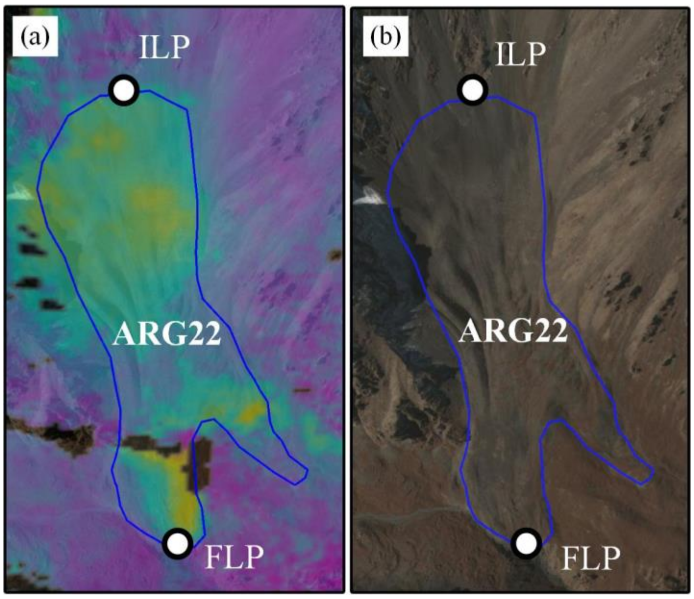

Fig. R1 ARG22 and its ILP and FLP. (a) shows the InSAR phase map for the ARG22, and the blue line denotes the active boundary determined from the phase variations. (b) shows the Google image.

- Some MARG mentioned in the manuscript, both ILP and FLP might be misreading, for example, ARG 95, the ILP is at glacier, the FLP should be down slope at 43.6226° N, 85.4043° E.

Authors: Thank you very much for your corrections. We have corrected the ILP and FLP for the ARG 95 based on the interpretation of historical images from the Google Earth. We have also checked the ILP/FLP for each identified ARG to improve the accuracy of our inventory.

- ARG 219, 220, and 221 seem merge ARG 157, form a combined RG, the FLP might reach forest zone – see Google Earth.

Authors: Some nearby ARGs could merge and form a combined rock glacier. In such cases, we classified each sub-ARG as individual rock glacier for following two reasons. (1) The sub-ARGs have different aspect angles. (2) We want to include the identified ARGs as many as possible. We have added one sentence to explain the combined ARGs in our revised manuscript, please see Lines 187-189.

(3) Surface velocity: It is better offering surface velocity by several years' data. In the discussion, comparing with Cui and Zhu, Zhu.

Authors: It is a good idea to map the surface velocities of ARGs using several year's SAR data. The multi-temporal observations would help us to reveal the seasonal fluctuations of the velocities of the ARGs (e.g., Liu et al., 2013). However, due to the rough topography in the NTS area, very few ALOS PALSAR interferometric pairs are suitable for InSAR time series analysis. The suitable interferometric pairs should have both small temporal span and perpendicular baseline, thus maintaining good phase coherence. In this study, we selected the PALSAR interferograms that have a temporal span of 46/92 days and perpendicular baselines smaller than 600 m. In addition, we only used the PALSAR images acquired in summer to form the interferograms except for the Path 503. We have added some descriptions about the SAR data we used in this study, please see Lines 136–140.

We have added a sub-section (Section 5.1) in the discussion part to compare our inventory with the previous studies. In which, we compared the surface velocities derived from our InSAR measurements with the field observations conducted by Cui and Zhu (1989) and Zhu (1992a). Please see Lines 409–435.

(4) Indication of lower limit of permafrost: Though the manuscript give detailed discussion, the estimated lower limit of permafrost is well below field survey (Qiu et al., 1983) might be caused by missing the small RGs, especially the talus derived ones.

Authors: Thank you for pointing out this possible reason that would influence the lower limit of permafrost we estimated. The InSAR phase maps we generated have a spatial resolution of about 15 meters. It is possible that some small rock glacier in the shadows of radar images cannot be identified. We have added this possible reason in the revised version (see Lines 259–268).

(5) References: Page 12, 4.4, references suggested: Jin HJ et al, 1993, Journal of Glaciology and Geocryology, 15(1). Qiu GQ, 1993, Journal of Glaciology and Geocryology, 15(1). Zhao L et al. 2010, Journal of Glaciology and Geocryology, 32(2).

Authors: Thanks for your suggestions. We have added these three references in the revised manuscript, please see Lines 372, 405–407.

3. Technical corrections: a compact listing of purely technical corrections, typing errors, typographical corrections, etc.

(1) Page 3 line 77-78: “There is a lack of studies on surface velocities of rock glaciers or an inventory containing the locations of the surveyed rock glaciers.” See Cui and Zhu 1989.

Authors: The relevant sentence has been rewritten as: “The studies on surface velocities of rock glaciers are very limited except for the field surveys at several specific sites conducted by Cui and Zhu (1989) and Zhu (1992a).”

(2) Page 4 line 97 (Zhu et al., 1992b) should add now reference. Zhao L. et al. 2010.

Authors: The reference of Zhao et al., (2010) has been added, please see Line 110.

(3) Page 4 line 102 "(Cui and Zhu, 1989; Zhu et al., 1992a, 1992b; Liu et al., 1995)" - (Cui and Zhu, 1989; Zhu, 1992a, Zhu et al, 1992b; Liu et al., 1995)

Authors: The citation format has been corrected in the revised version.

(4) Page 6 line 151-152 "Debris-covered glaciers are usually covered with uniformly thin debris layer, whereas rock glaciers debris cover is less homogenous and coarser." – What is the basis?

Authors: Considering the comments of the referee 3 (Dr. Bolch), we have rewritten the relevant sentences as follows (please see Lines 174–180):

"We distinguished ARGs from debris-covered glaciers based on the de-correlation conditions of interferograms and their different visual features on the Google Earth images. Compared with rock glaciers, debris-covered glaciers generally move much faster (Janke et al., 2015), which results in large areas of de-correlation in our PALSAR interferograms. The surface of a debris-covered glacier is usually characterized by ice cliffs and supra-glacial lakes (Bolch et al., 2007). And the rooting zones of debris-covered glaciers are continuous with clean glacier ice (Davies et al., 2013; Lukas et al., 2007)."

(5) Page 10 line 239 "IPLAs"? Not mentioned in the text.

Authors: This is a typo. "IPLAs" has been changed to "ILPAs".

(6) Page 11-12, 4.3 Surface velocities of the active rock glaciers Reference Cui and Zhu, 1989.

Authors: We have added a discussion subsection (Section 5.1) to compare our inventory with the previous studies of rock glaciers in the Tien Shan (Lines 409–435).

(7) Page 17 line 442-444. The paragraph (4) seems could be omitted.

Authors: We have removed the paragraph (4).

(8) Page 17 line 446-448 "This inventory offers a baseline dataset for the further investigations on permafrost modeling, slope stability, and water resource, etc." – why slope stability, and water resource? Not mentioned in the text.

Authors: We have added some descriptions and references in the "Introduction" part to clarify the significance of rock glaciers on the water resource in the semi-arid region and the potential hazards in the high mountains. Rock glaciers serve as important freshwater reserves because of the potential melting of their internal ice in the runoff season. Active rock glaciers may cause mass waste hazards on steep slopes when they move downslope, and thus threatening the sensible infrastructures in some downhill areas (Schoeneich et al., 2015). Please see Lines 31–33, 37–38.