Reply to comments by Tobias Bolch on "Mapping and inventorying active rock glaciers in the Northern Tien Shan (China) using satellite SAR interferometry"

We thank Dr. Bolch for his detailed and insightful review of the discussion paper. We have addressed all the comments and made the suggested changes in the revised version of our manuscript. Our point-by-point replies (in blue) to the critical comments (in black) are listed below.

The most important issues are:

- The delineation of the rock glaciers seems to be unprecise as e.g. visible from the figures: The upper boundary may be hard to define precisely but some more efforts should be made; is it not clear from Fig. 2 which criteria was used and the boundary is very probably not rectangular. It seems to me from Figs. 2b and 4 that exposed rocks are included. The lower boundary visible in Fig. 2b is also too rough as parts which clearly belong to the rock glacier are missed while others (e.g. even a part of the river were included). This needs to be improved as good as possible for all outlines so that at least no obvious errors are made.

Authors: We are grateful for the suggestions. We have checked the outline of each inventoried ARG and re-delineated some of them based on the InSAR phase and optical images. We also re-plotted Fig. 2 and Fig. 4 to correct the errors pointed out by the reviewer.

- Rock glaciers provide a hint where the lower limit of permafrost is located. However, the lower limit of rock glaciers varies significant due to topographic factors and the blocky material favors cooler temperatures allowing rock glaciers to exist at elevations where permafrost is otherwise unlikely (see. e.g. modelling studies for the Northern Tien Shan in Kazakhstan/Kyrgyzstan, see references). I'd therefore suggest rather to discuss the suitability of rock glaciers for investigation the permafrost occurrence (as you partly already did) than presenting new results of a lower limit of the permafrost occurrence which is highly uncertain. The authors should also keep in mind that there is no clear limit but that especially in mountains the permafrost occurrence is very heterogeneous.

Authors: Thanks very much for the insightful suggestion.

The purpose of this study is to propose a new method for inventorying active rock glaciers in the periglacial high mountains. We chose the Northern Tien Shan in China as a study area and then used the inventoried talus-derived active rock glaciers (TARGs) to infer the lower limit of permafrost. As suggested by the reviewer, there may be a high uncertainty in the estimates of permafrost limits due to the heterogeneous thermal region in mountainous environment. Previous studies conducted by Gorbunov et al. (2004) in Transili Alatau Tien Shan revealed a significant difference between the thermal regime of coarse blocky materials

and adjacent fine-grained soils. Mean annual temperatures inside the coarse debris could be 2.5–4.0 °C cooler than mean annual air temperatures (MAATs), which could cause rock glaciers occur at elevations where permafrost is unlikely to exist. However, the statistics of our inventory show that the MAAT at the TARGs is -5.4 °C, and 83 % of the TARGs have the MAAT lower than -4 °C. This indicates that the TARGs we used for estimating the lower limit of permafrost are in a cold environment, and thus reinforcing the credibility of the estimates. We now include such analysis and interpretation in the revised manuscript (Lines 456–459).

It is indeed important to discuss the suitability of rock glaciers for investigating the permafrost occurrence. An accurate permafrost distribution map will be helpful as a reference for this kind of investigation. However, the available permafrost distribution maps in our study (the IPA permafrost map, the CAS permafrost map, and the PZI map) all have very coarse spatial resolutions. Therefore, it is difficult to assess what characteristics of rock glaciers should have that would be suitable for inferring the permafrost distribution based on our present dataset. We decide to keep the original discussion on the lower limit of permafrost in the region, which is a range, and leave the use of individual rock glaciers for permafrost occurrence in the future work.

- There is limited discussion where the authors put their approach and results into context. There are several studies existing which were presenting rock glacier inventories and further information in the neighbouring Kazakh and Kyrgyz Tien Shan. Several ones are in Russian which might be difficult to understand (but may still be considered as they provide valuable information) but there are also several published in English (especially by A. Gorbunov, see references). One more recent paper co-authored by Gorbunov presents also a topographic analysis which would be very interesting to compare your results too.

Authors: We have added an addition discussion section (Lines 409–435) to compare our inventory with the previous studies of rock glaciers in the NTS (Cui and Zhu, 1989; Zhu, 1992a; Zhu et al., 1992b; Liu et al., 1995) and the Kazakh/Kyrgyz Tien Shan (Gorbunov et al., 1992, 1998). The rock glacier studies in the NTS conducted by Cui and Zhu (1989) and Zhu (1992a) reported that most of the identified rock glaciers are tongue-shaped, located at altitudes between 3300 m and 3900 m, and facing north, which are generally consistent with our inventory. The studies of rock glaciers in the Kazakh/Kyrgyz Tien Shan are concentrated in the Djungar Ala Tau, the Ile Alatau, and the Kungöj Ala-Too mountain ranges. The rock glaciers in the Djungar Ala Tau lay lower altitudes comparing to the NTS, probably due to their more northerly latitude. While the altitudinal distributions of the rock glaciers in Alatau and Kungöj Ala-Too are similar with that in the NTS. These previous studies also revealed a homogeneity pattern of the ARGs surface velocities.

Additionally, we found that the topographic analysis conducted by Bolch and Gorbunov (2014) was focusing on the influences of the contributing area parameters (e.g. its area or the headwall height) on the area and minimum altitudes of the rock glaciers. However, such contributing area parameters were not investigated in our inventory. Therefore, it is impractical to compare our results with the topographic analysis of Bolch and Gorbunov (2014).

- Recent findings show a clear seasonal behaviour of the surface velocity (e.g. Wirz et al. 2016). Hence, it is important to mention the acquisition period of the data used to calculate the velocity also in the text. The seasonal effect should also be considered in the discussion.

Authors: The ALOS PALSAR data we used were acquired between 2007 and 2009, and all the data were acquired in summer except for Path 503. Each interferogram spans 46 or 92 days. We state this explicitly in Section 3 (Lines 136 and 139) and Table 1. The seasonal effects may contribute to the spatial heterogeneity of the surface velocities due to the acquisition times for each image pairs are different. We state this point in the revised version in Lines 361–367.

- With respect to the discussion I suggest to include a separate discussion section where you put your approach and results into context of the existing literature. Currently, the discussion section contains only a comparison of the rock glacier derived permafrost estimates to permafrost distribution estimates.

Authors: Following this suggestion, we have added a separated discussion section (Section 5.1) to compare our approach and results with the previous studies of rock glaciers in Tien Shan (Lines 409–435).

- A minor but important point: The Tien Shan is a large mountain range stretching from Uzbekistan into China. Considering the Tien Shan as a whole using “Northern Tien Shan” is not correct. You should rather use “Northeastern Tien Shan” in the title and elsewhere.

Authors: The study area is completely located in China and is termed as “Northern Tien Shan” traditionally. We find very few papers use “Northeastern Tien Shan” in the literature. To avoid confusion, we have changed the “Northern Tien Shan” to “Northern Tien Shan of China” in the title through the paper.

Specific comments:

Abstract:

L10: Rock glaciers are widespread not only in western China but in the whole of Tien Shan.

Authors: We have revised the sentences (copied bellow), please see Lines 10–11.

“Rock glaciers are widespread in the Tien Shan Mountain. However, rock glaciers in the Chinese part of the Tien Shan have not been systematically investigated for more than two decades.”

L11: There are few recent studies, but your statement is true for Western China. Please correct.

Authors: Done. Please see Line 11.

L24: The approach is interesting for global rock glacier mapping and not only for western China.

Authors: We have rewritten the sentence to “…to map rock glaciers over mountain ranges globally” (Line 22).

1. Introduction:

L28: I am missing the classical monography by Barsch (Barsch 1996) in the references. I’d rather cite Haeberli et al. (2006) instead of 2010 here.

Authors: We have added the reference ‘Barsch (1996)’ in Line 28 and changed the reference ‘Haeberli (2010)’ to ‘Haeberli et al. (2006)’.

L36: Not sure if a definition of inactive and relict rock glaciers are needed here. This is a cryospheric journal where the readers should know such basic knowledge.

Authors: We removed the definitions of inactive and relict rock glaciers.

L45: Brenning (2005) already mentioned it and used the term intact for active and inactive rock glaciers. You would are able to distinguish which is a major advantage.

Authors: Here we want to express that it is difficult to differentiate active rock glaciers from inactive ones directly through visual interpretation. Thus we chose to keep the original wording, i.e. “active and inactive” (Line 46).

L47ff: You should mention also somewhere that multi-temporal optical images can and were also used to investigate rock glacier velocity (e.g. Gorbunov et al. 1992, by visual interpretation; Kääb et al. 1997 by feature tracking).

Authors: We have added some words to include the use of multi-temporal optical images for investigating the surface velocities of ARGs (Lines 61–63).

L68: Mention here at least one of the existing studies.

Authors: We have added two references (Kenyi and Kaufmann, 2003; Liu et al., 2013) (Line 69).

L74: Include here few of the existing studies of the Kazakh and Kyrgyz Tien Shan.

Authors: We have added several sentences (copied below) (Lines 75–80).

"Rock glaciers are abundant in the high mountains of Central Asia and western China, such as the Tien Shan, Hindu Kush Himalayan, Kunlun Shan and Hengduan Shan. More than 1500 rock glaciers have been inventoried in the Kazakh and Kyrgyz Tien Shan (Gorbunov et al., 1992;1998). Schmid et al. (2015) compiled an inventory with 702 rock glaciers identified from Google Earth images in the vast Hindu Kush Himalayan region. Using these inventories, recent studies have further discussed the rock glaciers-permafrost interactions (Bolch and Gorbunov, 2014; Schmid et al., 2015)."

L80: You may mention here the study by Bolch and Gorbunov for the nearby Northern Tien Shan in Kazakhstan and Kyrgyzstan and maybe also Schmid et al. (2015)

Authors: We have added citations to these papers (Line 80).

2. Study area:

General: Provide more details about the general characteristics of the Tien Shan, the subdivision, and especially the climatic conditions.

Authors: Thanks for your suggestions. We have added detail descriptions of the subdivision and climatic conditions of the Northern Tien Shan of China (Lines 97–99, 111–117).

L97: Be more specific about the annual precipitation amount. The west is wetter than the east but not really wet. The climate is only relative humid for the continental conditions.

Authors: We have added several sentences (copied below) in this section (Lines 111–117).

"There are two long-term meteorological stations in the NTS. The Daxigou meteorological station (86.84 °E, 43.11 °N) in the eastern part is at about 3540 m above sea level. The Snow-cover and Avalanche Research Station (SARS, 84.40 °E, 43.26 °N) lies in a valley in the western part of the NTS, at an elevation of about 1776 m. The mean annual air temperature (MAAT) and the mean annual precipitation around the Daxigou station were about −6 °C and 405 mm in 1990–2008, respectively (Sun et al., 2013). The MAAT near the SARS was about 1.3 ℃, falling to −9.4 ℃ at 3580 m. The mean annual precipitation at the SARS was about 830 mm (Shi et al., 2009)."

L102: You cite here almost the same studies than in L75 in the introduction. I suggest to cite in the intro those which provide information about the larger regions or from surrounding

ranges and in the study region section the specific ones.

Authors: Following the suggestion, we have rewritten the relevant sentences in introduction (Lines 75–80) and cited the studies of rock glaciers in the Kazakh and Kyrgyz Tien Shan and the Hindu Kush Himalayan region, such as Bolch and Gorbunov, 2014, Gorbunov et al., 1992, and Schmid et al., 2015.

3. Methodology:

General: The other reviewers are more experts in SAR processing. Therefore I will not comment on the technical aspects here. However, I'd like to see a better figure where the authors present the identification of moving surface based on the wrapped interferometric phase. Fig. 3 is interesting in this regard but I find it hard to understand how you identified surface displacements based on this image. Maybe a larger image or a zoom would help. Provide a short information about the quality and suitability of the images available at the time of the study in google earth, e.g. had all images good snow conditions and where all of very high resolution?

Authors: We have added two figures (Figure 3c and 3d) for showing the identification of the moving surface based on wrapped interferometric phase. Fig. 3c shows the outline of the rock glacier determined from the variations of phase map, and Fig. 3d shows the corresponding optical image for the rock glacier in Google Earth. Additionally, we selected the Google Earth images that were cloud free and were taken in summer season as the limited extent of snow cover to readily identify ARGs. We state this in the revised version in Lines 164–166.

L148: I agree that active rock glaciers have usually little or no vegetation, but not always (e.g. there are trees on rock glaciers in other parts of the Tien Shan). Hence, write "have usually little or no vegetation" or similar.

Authors: Corrected, please see Line 172.

L151: It is not true that debris-covered glaciers "are usually covered with uniformly thin debris layer". There are manifold studies which show that the debris thickness usually increases towards the terminus and that the surface of a debris-covered glacier is characterised by ice cliffs and supraglacial lakes. It is partly hard to distinguish clearly between debris-covered glaciers and rock glaciers as gradual transitions to moraine-derived rock glaciers exist especially in continental conditions.

Authors: Thanks for pointing out this. We have rewritten the relevant descriptions for the debris-covered glacier (copied below). 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)."

L161: What is a rooting zone "Z" and where is it in Fig. 1?

Authors: We have enlarged the denotation of the zone "Z" in Fig. 1.

L184f: I find the abbreviations ILP (initial line point) and FLP (front line point) not intuitive as you are mainly interested in the altitude. Humlum (1998) uses RILA (rock glacier initiation line altitude). As you are referring to the maximum and minimum altitude I'd use h_{min} and h_{max} . But you may decide.

Authors: Thanks for your suggestion. We define the ILP and FLP to conveniently determine the parameters of the inventoried ARGs, such as length, aspect, and slope. Therefore, we decide to keep the abbreviations.

L197f: It can be quite difficult to identify the upper boundary. Hence, InSAR is quite promising. Provide more details and examples for how you identified the upper boundary. Ridges and furrows are typical for compressive flow in the lower rock glacier area and, hence, you might have missed parts if you only use these criteria.

Authors: We now added one more example to show the InSAR-determined outline of an ARG, please see Figs. 3c and 3d and Lines 198–200.

L200: Should be Gruber (2012).

Authors: Corrected.

L206: Why do you mention "lower limit of the permafrost distribution" here. You are quantifying the rock glacier parameters.

Authors: We have rewritten the sentence (copied blow), please see Lines 243–244.

"The uncertainties of the FLP and ALP altitudes are determined by the errors of the SRTM digital elevation model, which has a nominal vertical accuracy of less than 16 m (Farr et al., 2004)."

4. Results:

L222f: Move to methods.

Authors: We have moved the sentence to the Method section (Lines 204–205).

L250ff: What is about the influence of the general topography? It could be worth to compare the aspects of the rock glaciers to the aspect distribution of the investigated mountain ranges. The aspect distribution of the rock glaciers in Kazakh and Kyrgyz Northern Tien Shan is clearly influences by the topography.

Authors: We calculated the aspect distribution of the mountain ranges in the study area and found the number of north-facing and south-facing slopes are similar. Therefore, we inferred that the topography in the NTS is not the controlling factoring for the aspect distributions of the MARGs. We presumed that the larger percentage of north-facing MARGs in their quantum than the TARGs is due to aspect distribution of the glaciers. While we noted that the majority of glaciers in the NTS are north-facing.

L252: Kaldybayev et al. (2016) investigate glaciers in Dzhungar Alatau which is close to you study region but is not the Northern Tien Shan.

Authors: Thanks for pointing out this. The reference "Kaldybayev et al., 2016" has been removed in the revised version.

L266: Be careful with the statement about the lower limit. See my general comment above.

Authors: We have added some word to declare the lower limit, please see our replies to the general comments.

L270: What is about the precipitation? I would assume the precip is also of importance.

Authors: Agree. We have rewritten the relevant sentences to state the possible influence of precipitation on the altitude distribution of rock glaciers (Lines 319–322).

L278f: This is an important point and should be discussed more in detail.

Authors: We have further discussed the different altitude distributions of ARGs in the western and eastern parts of the NTS. The paragraph reads now as follows (Lines 323–331):

"Additionally, we found different altitude distributions of ARGs in the western and eastern parts (Fig. 7a). The nearly linear pattern in the east is more apparent than that in the west. We performed a T-test on the similarity of the FLP altitude distributions in the two sub-regions. The P-value is smaller than 0.01 at the 95 % confidence level. Therefore, we conclude that the altitude distribution in the western NTS is significantly different from those located in the eastern part. The relatively scattering pattern in the west indicates that the altitude distributions of the ARGs there are not dominantly controlled by the geographical location

(i.e., longitudes). There could be other factors influencing the altitude distributions in the west. For instance, Bolch and Gorbunov (2014) revealed that the characteristics of the contributing area (e.g., the area, slope, and elevation range) of rock glaciers would influences their altitude distribution as well."

L280ff: You need to consider that the temperature in the blocky material of the rock glaciers can be significant colder than the MAAT (e.g. Gorbunov et al. 2004).

Authors: Thanks for pointing out this. We have rewritten the relevant sentences (copied below) to declare this (Lines 333–336).

"The highest correlation coefficient is found at the factor "MAAT". Although the blocky material of the rock glaciers may lower the ground temperature from the air temperature, this high correction implies that the MAAT may influence ground thermal conditions and thus the formation, evolution, and survival of the ARGs."

L287ff: The first lines of this section describe methods and should be presented in the methods section. In addition, as mentioned information about the time of the year when the velocity was measured are required.

Authors: We move the first sentence into the method section (Line 202). The times of the measured velocities are provided in Table 1.

L302f: The presence of water (e.g. from snow melt or heavy rain fall) has a strong influence on the short term variation. This should be mentioned and discussed along with the acquisition period of the data.

Authors: We now state the influences of precipitations on the derived ARGs surface velocities (Lines 365–367).

5. Discussion

I suggest a separate discussion section where you put your results into context. I suggest to slightly shorten the discussion about the comparison to the existing permafrost maps.

Authors: As suggested, we have shortened the discussion on the comparison of our results to the IPA and CAS permafrost maps.

6. Conclusions

Readers often read the abstract and look at the figures conclusion only before they decide to read the entire paper. I would therefore not use non-common abbreviations in the conclusions and figure captions.

Authors: We have removed the non-common abbreviations in the conclusions and figure captions, such as ARGs and NTS.

L434: Use one decimal digit only. The exact area is quite uncertain.

Authors: We have changed the area of ARGs with one decimal digit.

L442ff: Conclusion 4 is hard to understand.

Authors: Considering the comment of the first referee, we removed the Conclusion 4.

L446: The methods cannot only applied in China.

Authors: We have stated the method can be applied to the other high mountains globally (Line 532).

L450: Reformulate the last sentence. Rock glaciers provide a hint for permafrost occurrence but should be used with care when modelling permafrost distribution.

Authors: We have rewritten the sentence to be rigorous, please see Lines 532–533.