

Comment on esurf-2022-8

Authors response to Anonymous Referee #2

Dear Referee,

Please find in the following our answer to your comments.

Note that Referee comments are noted as “**RC** –“ and authors responses as “**AC** >”.

RC –The presentation of the recent rock glacier velocities based on image correlation needs revisions.

AC > The presentation of the recent rock glacier velocities based on image correlation has been revised.

RC – The description of the orthomosaic production needs revision. Without presenting the quality of the relevant parameters during orthorectification (e.g. GCPs accuracies, RMSE or SD, bundle block adjustments), the photogrammetric results are not comprehensible and meaningful.

AC > Then quality of the orthorectification and coregistration has been evaluated using 11 manual control point providing a mismatch of topographic feature on both orthomosaics. The IMCORR results haven also filtered using IMCORR parameters (xerr and yerr). Finally, 6 control areas have been defined to assess the quality of the feature tracking analysis.

RC – I suggest discussing and expanding the relevant literature in more detail (see the attached annotations). Furthermore, a table (or two) indicating all relevant parameters for each dataset (resolution, scale, number of GCPs, Tie-points per image, mean RMSE, among other parameters) should be provided

AC > The relevant literature has been discussed and expanded in more detail as suggested. Remote sensing analysis has been improved. First the ground control points (GCPs) accuracies, distribution has been provided and discussed (Figure A1 and Table A1).

We thank you for your comments and suggestions, the manuscript in its revised form has gained in quality both scientifically and clarity. Please find attached all our response to the detailed comments.

Best regards,

Benjamin Lehmann et al.

Detailed comment and answer:

RC - Line 12: Please, specify that you are talking about active - or intact - rock glaciers

AC > We specified that we are talking about active rock glacier.

RC - Line 13: This is somehow vague. What do you really mean with strongly influence (hydrological, geomorphological)?

AC > We specified the hydrological and geomorphological influence of rock glacier.

RC - Line 14: This is questionable. The quantification of the ground ice melt from rock glaciers and their role in the mountain runoff are rarely considered.

AC > In this sentence we are speaking about the "reserve" character as water storage of rock glacier and not the "resource"

RC -Lines 20-21: please consider: " Remotely sensed images and correlation techniques are used to document"

AC > This sentence has been updated following your recommendation, thanks.

RC -Line 21: Please, review this $10^1 = 10$

AC > This sentence has been changed for: "over timescales ranging from year to decades."

RC -Line 29: I do not see the need of using "rock-glacier" (with the hyphen). Please review this use thoroughly.

AC > All hyphens were removed according to suggestion

RC -Line 31: Please, remove Ka

AC > Removed as suggested.

RC -Line 38: What about the fall sorting, kinetic sieving and down-washing of fine sediments? Please, develop these ideas.

AC > To not to dive in complexity straight for the first sentence of introduction "Poorly-sorted" was removed.

RC -Line 41: What about rock glacier acceleration and destabilisation associated with rising air temperatures. This has been observed in many places (e.g. Marcer et al 2021)? Can we consider rock glaciers as resilient cryospheric bodies?

Marcer, M., Cicoira, A., Cusicanqui, D., Bodin, X., Echelard, T., Obregon, R. & Schoeneich, P. 2021. Rock glaciers throughout the French Alps accelerated and destabilised since 1990 as air temperatures increased. *Communications Earth & Environment* 2 : 81. DOI: 10.1038/s43247-021-00150-6

AC > This sentence was added to address the acceleration and destabilization you mentioned: “However, in-situ measurements since the last decades have shown rock glacier acceleration and destabilization associated with increasing air temperature in the European alps (e.g., Marcer et al. 2021).”

RC -Line 42: mountain glaciers

AC > Changed as suggested.

RC -Line 42: It is not easy to assess the importance of rock glaciers as water supplies from this Article. I recommend removing this reference.

AC > This reference has been removed as suggested.

RC -Line 43: Are rock glaciers eroding the headwalls? Please explain this.

AC > This sentence has been edited as such: “Over geological timescales, rock glaciers participate actively in the development of asymmetrical mountain crests by conveying rock from leeward headwalls (where rockfall is the primary source of debris) to lower elevations in the valley”.

RC -Line 44: The list of references needs some revision. The references Gilbert, 1904 and Johnson et al., 1980 are missing.

AC > Reference list has been updated.

RC -Line 50: the remnant of glacial deposits

AC > Changed as suggested.

RC - Lines 50-51: Please, consider including one documented case of this process by:

Monnier, S. & Kinnard, C. 2015. Reconsidering the glacier to rock glacier transformation problem: New insights from the central Andes of Chile. *Geomorphology* 238 : 47–55. DOI: 10.1016/j.geomorph.2015.02.025

AC > Reference included as suggested.

RC - Line 52: According to your second holistic view, this process will be likely quite short (few decades)

AC > Modified as suggested.

RC - Lines 54-55: Please, consider including:

Ikeda, A. & Matsuoka, N. 2006. Pebbly versus bouldery rock glaciers: Morphology, structure and processes. *Geomorphology* 73 : 279–296. DOI: 10.1016/j.geomorph.2005.07.015

AC > The reference was included as suggested.

RC - Line 60: This reference does not fit what has been declared in this sentence. Please, remove or adapt the sentence accordingly. Also, please specify that you are talking about European rock glaciers.

AC > The reference has been removed and specification of European rock glaciers included as suggested.

RC - Line 64: Please, review the use of Hyphens

AC > Hyphens were removed as suggested.

RC - Lines 67-69: This sentence is hard to read. Please, consider splitting it into two

AC > The sentence has been split in 3.

RC - Line 70: Please consider: "remote sensing tools for monitoring changes on high mountain landforms"

AC > Changed as suggested.

RC - Line 71: The work of Robson et al., 2020 does not really fit this sentence. However, the more recent work of Robson better fit this monitoring concept.

Robson, B.A., MacDonell, S., Ayala, Á., Bolch, T., Nielsen, P.R. & Vivero, S. 2022. Glacier and rock glacier changes since the 1950s in the La Laguna catchment, Chile. *The Cryosphere* 16 : 647–665. DOI: 10.5194/tc-16-647-2022

AC > Changed as suggested.

RC - Lines 74-77: It feels that this sentence is a little bit overstated. As Cusicanqui et al., 2021 only used orthorectified images derived from historical aerial photographs and recent UAV surveys, declaring satellite images seems inadequate and not right. Also, surface velocities are normally reconstructed using co-registered orthorectified images and not DEMs. I suggest reviewing the following references for additional insights into rock glacier surface velocities using image correlation techniques:

Kääb, A., Strozzi, T., Bolch, T., Caduff, R., Trefall, H., Stoffel, M. & Kokarev, A. 2021. Inventory and changes of rock glacier creep speeds in Ile Alatau and Kungöy Ala-Too, northern Tien Shan, since the 1950s. *The Cryosphere* 15 : 927–949. DOI: 10.5194/tc-15-927-2021

Vivero, S., Bodin, X., Farías-Barahona, D., MacDonell, S., Schaffer, N., Robson, B.A. & Lambiel, C. 2021. Combination of Aerial, Satellite, and UAV Photogrammetry for Quantifying Rock Glacier Kinematics in the Dry Andes of Chile (30°S) Since the 1950s. *Frontiers in Remote Sensing* 2 : 1–17. DOI: 10.3389/frsen.2021.784015

Fleischer, F., Haas, F., Piermattei, L., Pfeiffer, M., Heckmann, T., Altmann, M., Rom, J., Stark, M., Wimmer, M.H., Pfeifer, N. & Becht, M. 2021. Multi-decadal (1953–2017) rock glacier kinematics analysed by high-resolution topographic data in the upper Kaunertal, Austria. *The Cryosphere* 15 : 5345–5369. DOI: 10.5194/tc-15-5345-2021

AC > We thanked the reviewer for pointing out these problems, and for providing the references. Changes have been done as suggested.

RC - Line 78: Please, consider the work by:

Frauenfelder, R. & Kääb, A. 2000. Towards a paleoclimatic model of rock-glacier formation in the Swiss Alps. *Annals of Glaciology* 31 : 281–286. DOI: 10.3189/172756400781820264

AC > Reference included as suggested.

RC - Line 84: Please consider: in old permafrost cores from a rock glacier

AC > Changed as suggested.

RC - Lines 109-110: photogrammetry is a subset of remote sensing.

AC > The sentence was changed for "Remote-sensing approach such as image correlation over photogrammetric products allow us to reconstruct the surface displacements field of the rock glacier over the last six decades."

RC - Line 112: Please clarify: It is unclear whether the sampling was done right on the headwall or below it.

AC > We did not sample the headwall. This was changed to "its highest part".

RC - Line 115: Consider "proxies"

AC > Changed as suggested.

RC - Line 118: Barre des Écrins is the only 4000 m on this massif. Please, clarify this

AC > The sentence was completed with the following "with its highest summit being the only one above 4000 m a.s.l. (Barre des Ecrins, 4101 m a.s.l.)".

RC - Line 126: Please check this reference

AC > Those references of unpublished data have been removed.

RC - Line 126: glacierized terrain

AC > Changed as suggested.

RC - Line 131: from

AC > Changed as suggested.

RC - Line 131: to

AC > Changed as suggested.

RC - Line 131: Use either "rooting zones" or "root zones"

AC > Changed for "rooting zones".

RC - Line 134: since

AC > Changed as suggested.

RC - Line 149: it would be better to show such values in km².

AC > Converted in km² as suggested.

RC - Lines 153-154: This is unclear. please review this

AC > this part has been deleted for clarity.

RC - Lines 166-167: DEM and landscape image analysis are not part of your field observations. Please review this section.

AC > The name of the section was changed for "Geomorphological mapping/identification".

RC - Lines 173-174: I would suggest employing "landform" for your entire rock glacier system. Ridges and furrows should be catalogued as parts of your landform.

AC > "Landforms" was changed for "ridges" in the entire manuscript.

RC - Line 174: Please, review if you are using orthomosaics (2 or more images) or orthoimages (1 image).

AC > Here we are using "orthomosaics", thanks for the clarification.

RC - Lines 175-176: This sentence should be removed or reformulated. The image correlation protocol was originally presented by Scambos et al. (1992) and not Cusicanqui et al. (2021). Also, image correlation is not part of the orthomosaic production.

AC > This sentence was modified by "The reconstruction of the rock glacier surface displacement over decade timescales is done using image correlation protocol between different orthomosaic."

RC - Line 180: Please, include the location of these GCPs on figure 1a

AC > Details of the GCPs have been included in Figure A1 and Table A1.

RC - Line 180: coordinates

AC > Corrected, thanks for spotting this typo.

RC - Line 181: LiDAR surveys normally provide information in 3D point clouds. Please, specify if you are using the original point cloud to extract GCPs or a derived product such as a DSM. In the latter case, please also provide the interpolation method from point clouds to raster grid.

AC > Details about the DSM have been added as suggested.

RC - Line 183: Pléaïdes

AC > Changed as suggested.

RC - Line 185: Please, specify which DEMs and orthoimages are coregistered. Also, review the difference between DEM and DSM. From what is declared, I only see the LiDAR DSM. Are you talking about the Pléiades-derived DEM?

AC > Here only orthomosaic were coregistered. Sorry for this mistake.

RC - Line 187: orthoimages are 2D (x and y); therefore, I do not see the need of using the z coordinated during the shift.

AC > Thanks for spotting this mistake, this was corrected.

RC - Lines 196-197: where are those accurate results presented? If you want to express the displacement values in imcorr, the velocity will help to recude the error as the time interval increases.

AC > Only 1960 and 2018 were kept for the remote sensing analysis. Other orthomosaics are not mentioned anymore in the revised manuscript.

RC - Lines 197-198: Why not use the earlier grid space =4m? using the same grid size among the different combinations of orthoimages ensures that the same points are concurrent.

AC > This part has been removed as only 1960 and 2018 orthomosaics were kept in the study.

RC - Lines 199-201: What about the IMCORR error estimates for x and y directions? Why not use those statistics provided by IMCORR to filter your dataset?

AC > We re-analysed the IMCORR results and proceeded to a first phase of selection with a threshold of 100 pixels for xerr and yerr (error in x and y directions).

RC - Lines 201-202: Please, provide the % of points removed for all pairs

AC > As mentioned before, we only kept the 1960 and 2018 pair.

RC - Lines 204-205: What is the vegetation cover (green patch) impact inside this assumed “stable terrain.”?

AC > More work has been done on this part. The displacements obtained on the rock glacier system are compared to the measured displacements of 6 control areas where no displacement should be observed. Details of those control area are given in Figures 3, A1, A2 and Table A3. These control areas have been chosen to be outside of and around the rock glacier system and out of the scree field. The absence of movement (solifluction, creeping, landsliding) has been determined by visually inspecting historical aerial photographs collected from the IGN-France and the two orthomosaics.

RC - Line 210: features

AC > "Landforms" was changed for "ridges".

RC - Line 217: Maybe, you should clarify that the rock glacier displays or evidence a passive transport of the blocky material.

AC > The geomorphological evidence of activity has been already described in Section 4.1.

RC - Line 275-277: The statistics of this stable terrain need revisions. The error budget should account for the different components (e.g. shifts between images, orthorectification quality and image matching uncertainties). Please, review the recent work by Käab et al. (2021) for a better evaluation of your errors

Käab, A., Strozzi, T., Bolch, T., Caduff, R., Trefall, H., Stoffel, M. & Kokarev, A. 2021. Inventory and changes of rock glacier creep speeds in Ile Alatau and Kungöy Ala-Too, northern Tien Shan, since the 1950s. *The Cryosphere* 15 : 927–949. DOI: 10.5194/tc-15-927-2021

AC > The analysis of the uncertainties of the remote sensing treatment has been improved as suggested. Here is the revised section: “Figures 3, 4 and 5 present the results obtained using the IMCORR feature-tracking module. The surface displacement of the control areas (dashed outlined area in Figures 3 and A1) within stable terrain shows a median displacement of 0.79 ± 0.43 m (Figures 4g, A2 and Table A3). This value represents the accumulation of error from the orthomosaic production and the image correlation procedure. The quality of the orthomosaic production can be assessed using the statistic on the GCPs showing a median absolute error of 0.57 ± 0.34 m (Table A1) and the manual control points presenting a median mismatch distance between the two orthomosaics of about 1.04 ± 0.45 m (Figure 4h and Table A2).”

RC - Lines 277-278: I am afraid I have to disagree with this statement. Failed correlation (or better false correlations) can also be above the threshold values.

AC > This part has been changed for: “This last value, being the highest of the three error estimations, is use hereafter as a threshold value to control the confidence level of our remote sensing analysis and should be considered as detection limit. Consequently, all rock glacier areas showing surface displacement lower than 1.04 m and are consequently below the detection level (dashed area in Figure 5).”

RC - Lines 278-279: Rather than considered stable, these areas are below your level of detection.

AC > Modified as suggested.

RC - Line 322: Please review this reference. Amschwand et al. 2021

AC > Reference has been reviewed as suggested.

RC - Lines 381-284: You might argue about the representativeness of your different methods (single trajectory versus area based). Image correlation provides an area-wide velocity, which might be impacted by some boundary regions (i.e slow velocities). On the other hand, the velocities from surface-exposure dating represent the travel of the boulder from different zones since the detachment from the headwalls.

AC > This part has been added to the discussion: “Those observations should be put in perspective, the remote sensing analysis for each provides an estimation on the entire area of the unit. Consequently, the median velocity of the area might be affected by the friction at the boundary conditions. On the other hand, the velocity estimated from the ¹⁰Be surface-exposure dating have been calculated from samples collected at the center of the rock glacier system, where the surface velocity is supposed to be the fastest regarding a transversal cross section.”

RC - Lines 480-481: you might consider the work done by:

Humlum, O. 2000. The geomorphic significance of rock glaciers: Estimates of rock glacier debris volumes and headwall recession rates in West Greenland. *Geomorphology* 35 : 41–67. DOI: 10.1016/S0169-555X(00)00022-2

AC > This reference has been included as suggested.

RC - Lines 609-614: These entries are the same reference. Please review this.

AC > The reference list has been reviewed as suggested.

RC - Figure 3: These arrows are very difficult to read. Please, reconsider to change the arrow symbols /scale for a better visualization.

AC > The figure has been changed and revised.