CCI+ PHASE 2
PERMAFROST

CCN4
MOUNTAIN PERMAFROST: ROCK GLACIER INVENTORIES (ROGI) AND ROCK GLACIER VELOCITY (RGV) PRODUCTS

D3.2 Climate Research Data Package (CRDP)

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Executive summary

The European Space Agency (ESA) Climate Change Initiative (CCI) is a global monitoring program, which aims to provide long-term satellite-based products to serve the climate modelling and climate user community. The objective of the ESA CCI Permafrost project (Permafrost_cci) is to develop and deliver the required Global Climate Observation System (GCOS) Essential Climate Variables (ECV) products, using primarily satellite imagery. The two main products associated to the ECV Permafrost, Ground Temperature (GT) and Active Layer Thickness (ALT), were the primary documented variables during Permafrost_cci Phase 1 (2018–2021). Following the ESA Statement of Work for Permafrost_cci Phase 2 (2022–2025) [AD-1], GT and ALT will be complemented by a new ECV Permafrost product: Rock Glacier Velocity (RGV). This document focuses on the mountain permafrost component of the Permafrost_cci project and the dedicated rock glacier products.

In periglacial mountain environments, permafrost occurrence is patchy and the preservation of permafrost is controlled by site-specific conditions, which require the development of dedicated products as a complement to GT and ALT measurements and permafrost models. Rock glaciers are the best visual expression of the creep of mountain permafrost and constitute an essential geomorphological heritage of the mountain periglacial landscape. Their dynamics are largely influenced by climatic factors. There is increasing evidence that the interannual variations of the rock glacier creep rates are influenced by changing permafrost temperature, making RGV a key parameter of cryosphere monitoring in mountain regions.

Two product types are therefore proposed by Permafrost_cci Phase 2: Rock Glacier Inventories (RoGIs) and Rock Glacier Velocity (RGV) time series. This agrees with the objectives of the International Permafrost Association (IPA) Action Group on *Rock Glacier Inventories and Kinematics* (RGIK) [RD-5] and concurs with the recent GCOS and GTN-P decisions to add RGV time series as a new product of the ECV Permafrost to monitor changing mountain permafrost conditions [AD-2 to AD-4]. RoGI is an equally valuable product to document past and present permafrost extent. It is a recommended first step to comprehensively characterise and select the landforms that can be used for RGV monitoring. RoGI and RGV products also form a unique validation dataset for climate models in mountain regions, where direct permafrost measurements are very scarce or lacking. Using satellite remote sensing, generating systemic RoGI at the regional scale and documenting RGV interannual changes over many landforms become feasible. Within Permafrost_cci, we mostly use Synthetic Aperture Radar Interferometry (InSAR) technology based on Sentinel-1 images that provide a global coverage, a large range of detection capability (mm–cm/yr to m/yr) and fine spatio-temporal resolutions (tens of m pixel size and 6–12 days of repeat-pass). InSAR is complemented at some locations by SAR offset tracking techniques and spaceborne/airborne optical photogrammetry.

This Climate Research Data Package (CRDP) describes the status of the RoGI and RGV generation for CCI CCN4 iteration 1 and the plan for future work. We briefly present the current results of the RoGI multi-operator exercise and show the first pilot products of the RGV generation using InSAR. The preliminary results are also provided as data packages in attachment of the report. Both products follow the specifications defined in the PSD [RD-2] and will be further described and discussed in the upcoming PUG and PVIR (Deliverable D4.1 and D4.2 in February 2024).

1 Introduction

1.1 Purpose of the document

The mountain permafrost component of Permafrost_cci Phase 2 focuses on the generation of two products: Rock Glacier Inventory (RoGI) and Rock Glacier Velocity (RGV). The Climate Research Data Package (CRDP) describes the status of the RoGI and RGV generation for CCI CCN4 iteration 1 and the plan for future work.

1.2 Structure of the document

Section 1 provides information about the purpose and background of this document. Section 2 described the RoGI and RGV products generated during CCI CCN4 iteration 1. Section 3 explains the work that is foreseen in the future. A bibliography complementing the applicable and reference documents (Sections 1.3 and 1.4) is provided in Section 4.1. A list of acronyms is provided in Section 4.2. A glossary of the commonly accepted permafrost terminology can be found in [RD-17]. The CRDP also contains two Annexes with additional figures showing examples of the generated RoGI and RGV products.

1.3 Applicable documents

[AD-1] ESA. 2022. Climate Change Initiative Extension (CCI+) Phase 2 – New Essential Climate Variables – Statement of Work. ESA-EOP-SC-AMT-2021-27.

[AD-2] GCOS. 2022. The 2022 GCOS Implementation Plan. GCOS – 244 / GOOS – 272. Global Observing Climate System (GCOS). World Meteorological Organization (WMO).

[AD-3] GCOS. 2022. The 2022 GCOS ECVs Requirements. GCOS – 245. Global Climate Observing System (GCOS). World Meteorological Organization (WMO).

[AD-4] GTN-P. 2021. Strategy and Implementation Plan 2021–2024 for the Global Terrestrial Network for Permafrost (GTN-P). Authors: Streletskiy, D., Noetzli, J., Smith, S.L., Vieira, G., Schoeneich, P., Hrbacek, F., Irrgang, A.M.

1.4 Reference Documents

[**RD-1**] Rouyet, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D1.1 User Requirement Document (URD), v1.0. European Space Agency.

[RD-2] Rouyet, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D1.2 Product Specification Document (PSD), v1.0. European Space Agency.

[RD-3] Rouyet, L., Echelard, T., Schmid, L., Barboux, C., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D2.2 Algorithm Theoretical Basis Document (ATBD), v1.0. European Space Agency.

[RD-4] Delaloye, R., Barboux, C., Bodin, X., Brenning, A., Hartl, L., Hu, Y., Ikeda, A., Kaufmann, V., Kellerer-Pirklbauer, A., Lambiel, C., Liu, L., Marcer, M., Rick, B., Scotti, R., Takadema, H., Trombotto Liaudat, D., Vivero, S., Winterberger, M. 2018. Rock glacier inventories and kinematics: a new IPA Action Group. Proceedings of the 5th European Conference on Permafrost (EUCOP), Chamonix, 23 June – 1st July 2018.

[RD-5] RGIK. 2022. Towards standard guidelines for inventorying rock glaciers: baseline concepts (version 4.2.2). IPA Action Group Rock glacier inventories and kinematics, 13 pp.

[RD-6] RGIK. 2022. Towards standard guidelines for inventorying rock glaciers: practical concepts (version 2.0). IPA Action Group Rock glacier inventories and kinematics, 10 pp.

[RD-7] RGIK. 2022. Optional kinematic attribute in standardized rock glacier inventories (version 3.0.1). IPA Action Group Rock glacier inventories and kinematics, 8 pp.

[RD-8] RGIK. 2023. InSAR-based kinematic attribute in rock glacier inventories. Practical InSAR guidelines (version 4.0). IPA Action Group Rock glacier inventories and kinematics, 33 pp.

[RD-9] RGIK 2023. Rock Glacier Velocity as an associated parameter of ECV Permafrost: baseline concepts (version 3.2). IPA Action Group Rock glacier inventories and kinematics, 12 pp.

[RD-10] RGIK. 2023. Rock Glacier Velocity as an associated parameter of ECV Permafrost: practical concepts (version 1.2). IPA Action Group Rock glacier inventories and kinematics, 17 pp.

[RD-11] RGIK. 2023. Instructions of the RoGI exercises in the Goms and the Matter Valley (Switzerland). IPA Action Group Rock glacier inventories and kinematics, 10 pp.

[RD-12] Bertone, A., Barboux, C., Delaloye, R., Rouyet, L., Lauknes, T. R., Kääb, A., Christiansen, H. H., Onaca, A., Sirbu, F., Poncos, V., Strozzi, T., Caduff, R., Bartsch, A. 2020. ESA CCI+ Permafrost Phase 1 – CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D4.2 Climate Research Data Package Product Specification Document (CRDP), v1.0. European Space Agency.

[RD-13] Sirbu, F., Onaca, A., Poncos, V., Strozzi, T., Bartsch, A. 2022. ESA CCI+ Permafrost Phase 1 – CCN1 & CCN2. Rock Glacier Kinematics in the Carpathians (CCN1 Budget Extension). Climate Research Data Package Product Specification Document (CRDP), v1.0. European Space Agency.

[RD-14] Bertone, A., Barboux, C., Bodin, X., Bolch, T., Brardinoni, F., Caduff, R., Christiansen, H. H., Darrow, M. M., Delaloye, R., Etzelmüller, B., Humlum, O, Lambiel, C., Lilleøren, K. S., Mair, V., Pellegrinon, G., Rouyet, L., Ruiz, L., Strozzi, T. 2022. Incorporating InSAR kinematics into rock glacier inventories: insights from 11 regions worldwide. The Cryosphere. 16, 2769–2792. https://doi.org/10.5194/tc-16-2769-2022.

[RD-15] Pellet, C., Bodin, X., Cusicanqui, D., Delaloye, R., Kaufmann, V., Noetzli, J., Thibert, E., Vivero, S., & Kellerer-Pirklbauer, A. (2023). Rock glacier velocity. In State of Climate 2022 (Vol. 104, pp. 41–42). https://doi.org/10.1175/2023BAMSStateoftheClimate.1.

[RD-16] Adler, C., P. Wester, I. Bhatt, C. Huggel, G.E. Insarov, M.D. Morecroft, V. Muccione, and A. Prakash. 2022. Cross-Chapter Paper 5: Mountains. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2273–2318. https://doi.org/10.1017/9781009325844.022.

[RD-17] van Everdingen, R. Ed. 1998, revised in May 2005. Multi-language glossary of permafrost and related ground-ice terms. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. http://nsidc.org/fgdc/glossary.

2 Overview of the mountain permafrost data package

2.1 Rock glacier inventory (RoGI)

As described in the PSD [RD-2] and ATBD [RD-3], we performed a RoGI multi-operator exercise in 12 areas selected in 10 countries and 5 continents (Figure 1). The inventory teams are composed of 5 to 10 operators (incl. the PI). The exercise involved in total 40 persons. The work was performed in similar QGIS projects, with common file structure, background data and dialog boxes for semi-automatic attribute filling.

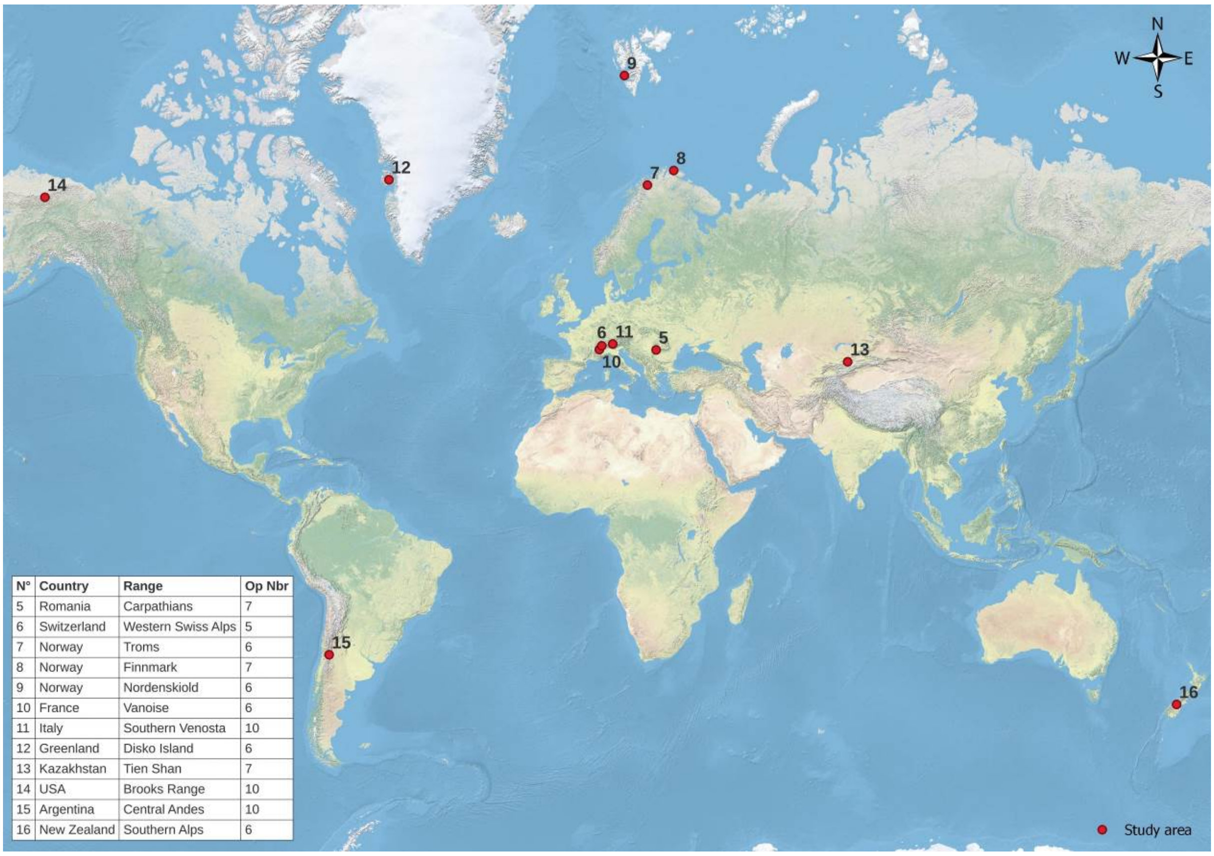

Figure 1: Location map of areas selected for the RoGI multi-operator exercise (the area numbering corresponds to the format defined in the PSD [RD-2]).

The inventorying procedure follows up on prior work aiming to reduce discrepancies between different operators and produce homogenous consensus-based RoGIs (Brardinoni et al., 2019; Way et al., 2021). The work has been performed in two steps:

- First part (June–Sept. 2023): the operators individually identified rock glacier units (RGU) with primary markers (PM) and detected potential moving areas (MA) based on Synthetic Aperture Radar Interferometry (InSAR) data. In each area, the PI compared the individual results and suggested final solutions. After discussion during a digital meeting with the operators, consensus-based PMs/MAs were adopted.
- Second part (Sept–Nov. 2023): Based on the consensus-based results from Phase 1, the operators outlined and documented the morpho-kinematics characteristics of the RGUs. In each area, the PI compared the results and suggested final solutions. After discussion during a digital meeting with the operators, consensus-based PMs (incl. attributes) and outlines were adopted.

The procedure is further explained in the ATBD [RD-3] and follows the inventorying rules defined by RGIK [RD-5, RD-6, RD-7, RD-8]. Examples of results (primary marker identifying the location of rock glacier units, outlines delineating the extent of the rock glacier units and moving areas used to assign a kinematic attribute) are shown in Figures 2–4. Other examples for each subarea are shown in Annex 1. The examples are selected in subsets of the inventoried areas for sake of visualisation. The generation of these maps has been automated in QGIS using Google Satellite, Bing Satellite and ESRI Satellite online services for the background optical images. It should be noted that in some areas, additional data sources with better quality and higher resolution have been used by the operators, especially for delineating the outlines. For the delineation of moving areas, the operators used a large set of InSAR data, mostly based on Sentinel-1 and complemented by ALOS-2 PALSAR-2, SAOCOM, Cosmo-SkyMed and TerrSAR-X interferograms (when available).

The data package provided in attachment of this report includes the individual results of both phases and the current consensus-based solutions for 12 areas. These results must still be considered as preliminary, as a comprehensive quality check is still required. Individual operator results will not be modified in the future, but the final consensus-based solutions may still be adjusted to correct formal errors and harmonise the products within and between the areas.

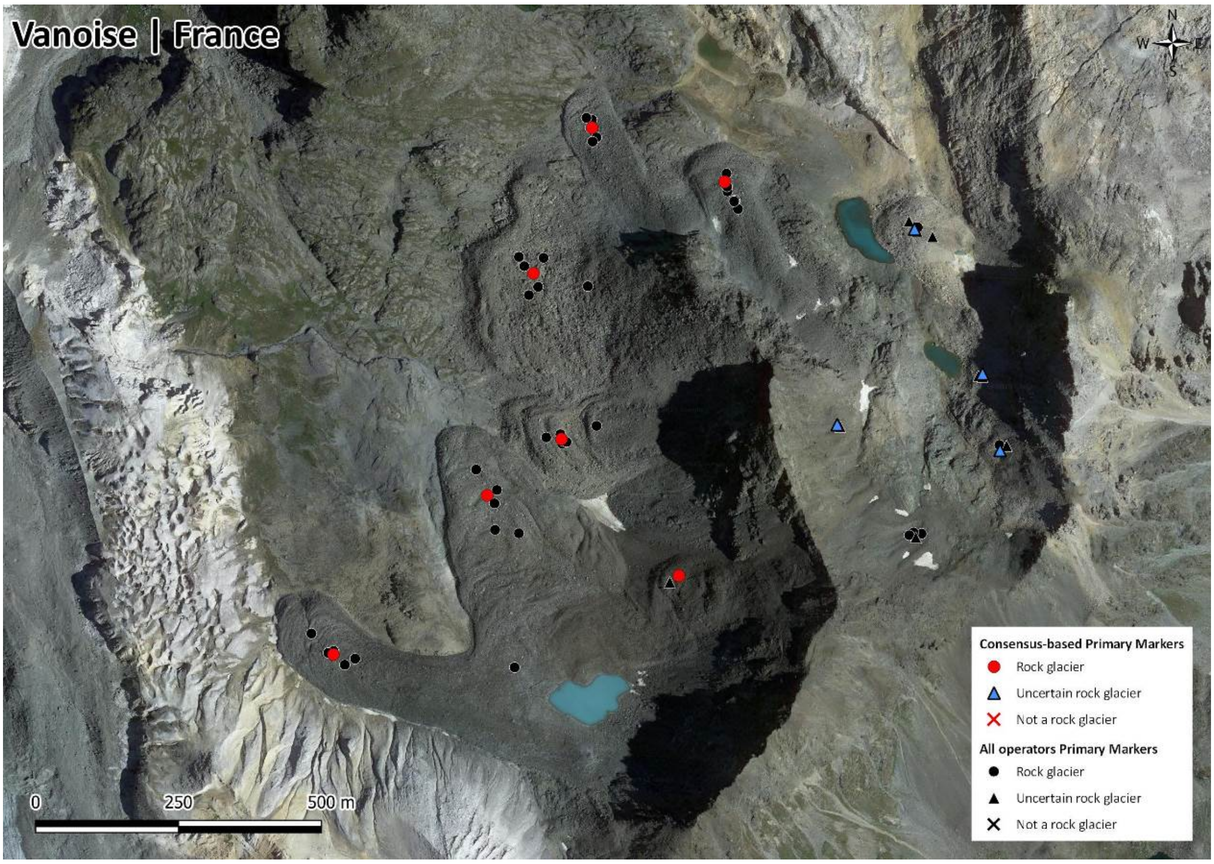

Figure 2: Example of Primary Markers identifying the location of rock glacier units in part of the Vanoise area (France). The black markers show the results of all individual operators. The red dots (certain rock glaciers), the blue triangles (uncertain rock glaciers) and the red crosses (not a rock glacier) show the consensus-based results after a meeting discussing the discrepancies between operators. Background orthophoto: Google Satellite Service. Note that the exercise included other imageries with different qualities and resolutions. See Annex 1 for similar examples in the other regions.

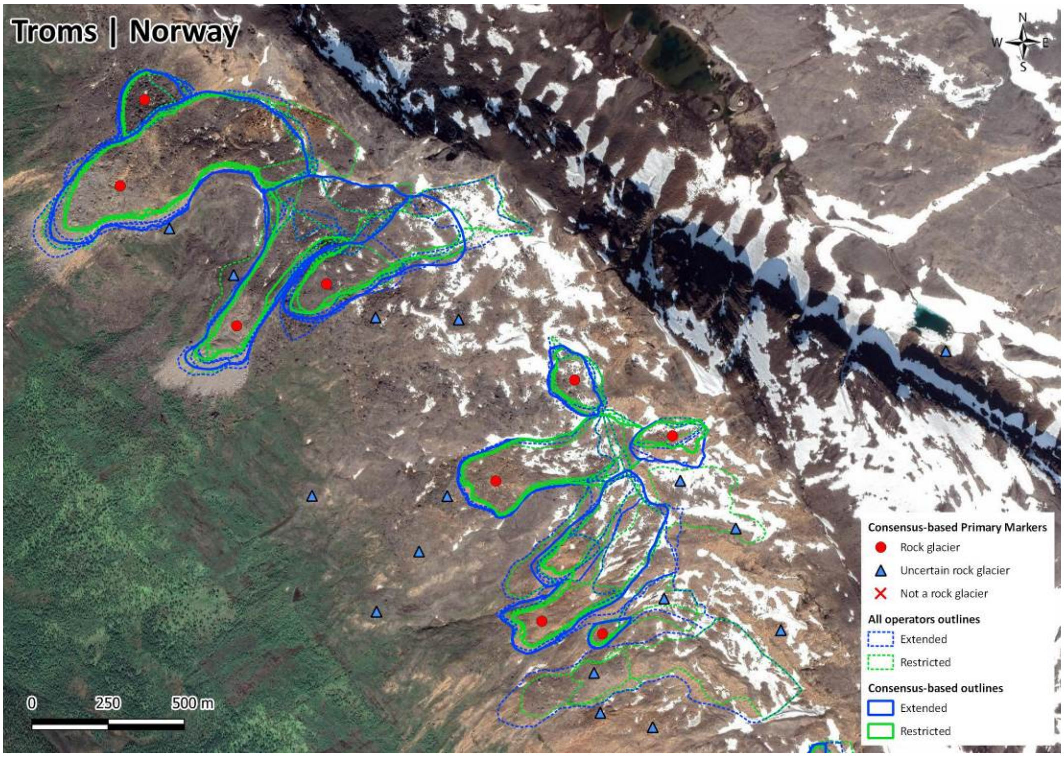

Figure 3: Example of rock glacier outlines for the certain rock glacier units (red dots) in part of the Troms area (Norway). The dashed lines show the results of all individual operators. The bold lines show the consensus-based results after a meeting discussing the discrepancies between operators. Background orthophoto: Google Satellite Service. Note that the exercise included other imageries with different qualities and resolutions. See Annex 1 for similar examples in the other regions.

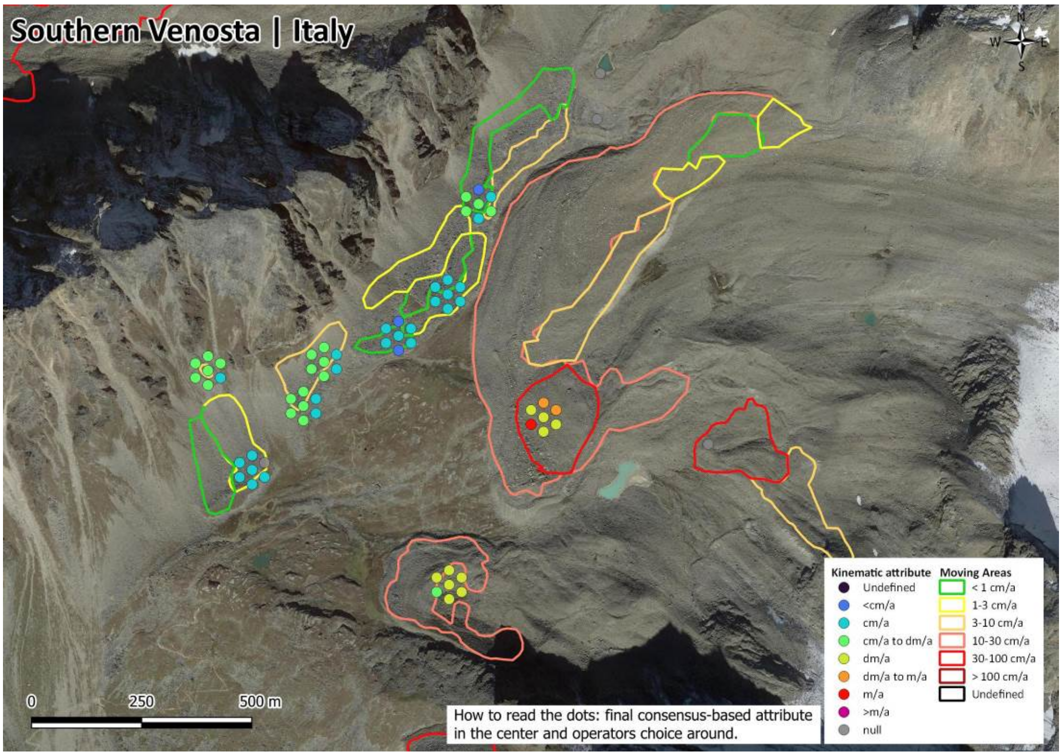

Figure 4: Example of InSAR-based Moving Areas and kinematic attributes associated to the certain rock glaciers (red dots), in part of the Southern Venosta area (Italy). The displayed Moving Areas are the consensus-based final results. Background orthophoto: Google Satellite Service. Note that the exercise included other imageries with different qualities and resolutions. See Annex 1 for similar examples in the other regions.

2.2 Rock glacier velocity (RGV)

As described in the PSD [RD-2] and ATBD [RD-3], Sentinel-1 InSAR has been processed over selected sites in the Swiss Alps. The results correspond to time series of annualized surface velocity, following the RGV requirements [AD-3, AD-4] [RD-9, RD-10]. The final product results from the temporal averaging of a large set of unwrapped interferograms and the spatial averaging of many time series over the rock glaciers (after filtering and clustering) The resulting InSAR-derived RGV document interannual trends of velocity changes assumed to be representative of the rock glacier units. We aimed to automate the procedure to enable the systematic monitoring of many rock glaciers in the future. This new method to generate InSAR-derived RGV and the discussion of the pilot results are part of a M.Sc. study to be completed in early 2024 (Schmid, in prep.).

Figure 5–6 show the InSAR-based RGV for the four sites. The individual results for the four sites are shown in Annex 2. Despite variable absolute velocity [m/a], the relative changes are quite similar. The results fit well with the observed trend based on in-situ data from the Swiss Permafrost Monitoring Network (PERMOS, 2023). Further intercomparison with existing complementary datasets will be included in the PVIR.

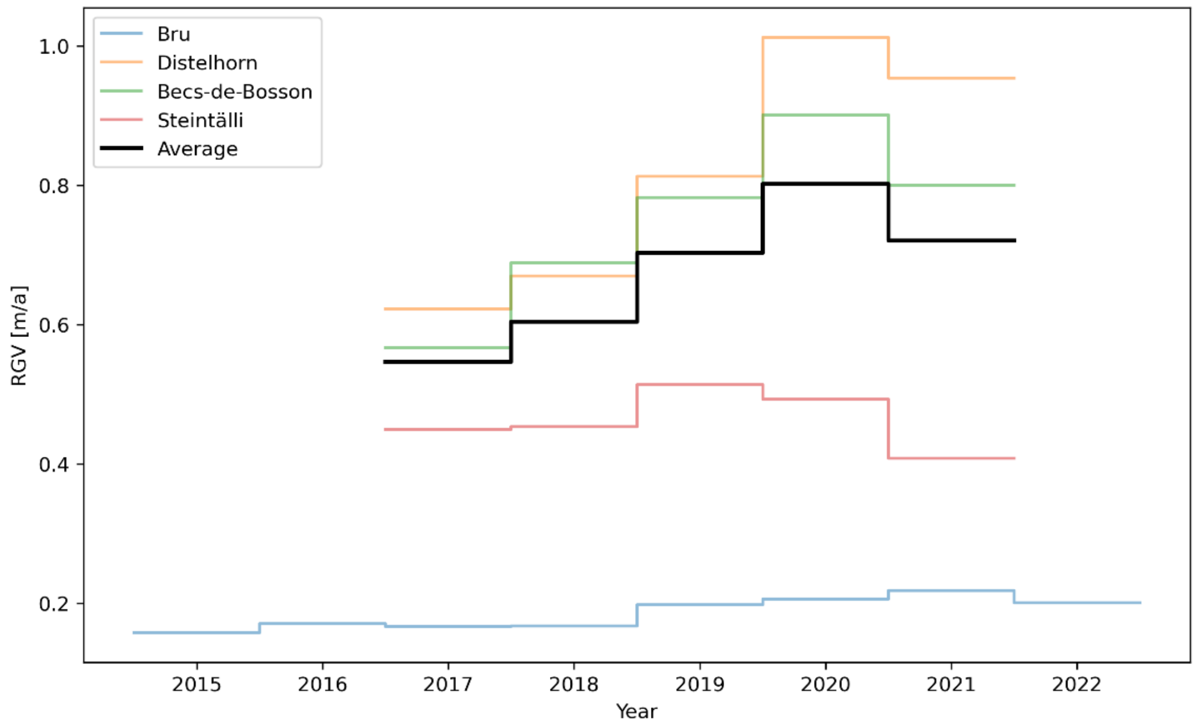

Figure 5: RGV products in m/a for four rock glaciers, between 2017–2021 for Distelhorn, Becs-de-Bosson and Steintälli and between 2015–2022 for Bru. The average of the four RGV products is represented by the black line. From Schmid (in prep).

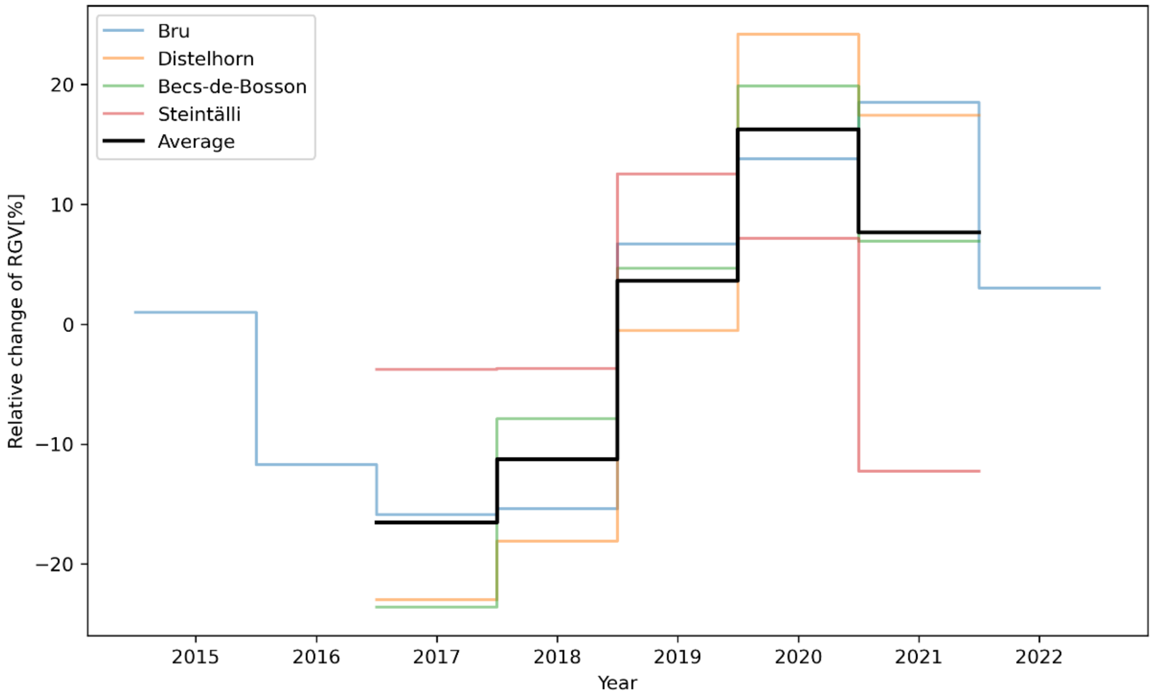

Figure 6: Relative change of RGV in % for four rock glaciers, relative to the overall time period (2017–2021 for Distelhorn, Becs-de-Bosson and Steintälli, 2015–2022 for Bru). The average is represented by the black line. From Schmid (in prep).

In addition, 44 Swiss rock glaciers have been analysed based on visual interpretation of wrapped interferograms using TerraSAR-X, ALOS-1, PALSAR-1, Cosmo-SkyMed, ALOS-2 PALSAR-2 and Sentinel-1 data. This is the follow-up of a study that show a good agreement between this InSAR interpretation and GNSS data between 2011 and 2017 (Figure 7, Barboux et al., 2019). The results have been updated with recent SAR images up to 2022 and the results show an overall concomitant behaviour (Figure 8), consistent with results from the automated method at the 4 sites (Figures 5–6, velocity peak in 2020). Due to the manual interpretation, these additional results are not following the methodology described in the ATBD [RD-3]. However, this complementary dataset will be valuable for future cross-validation in the PVIR.

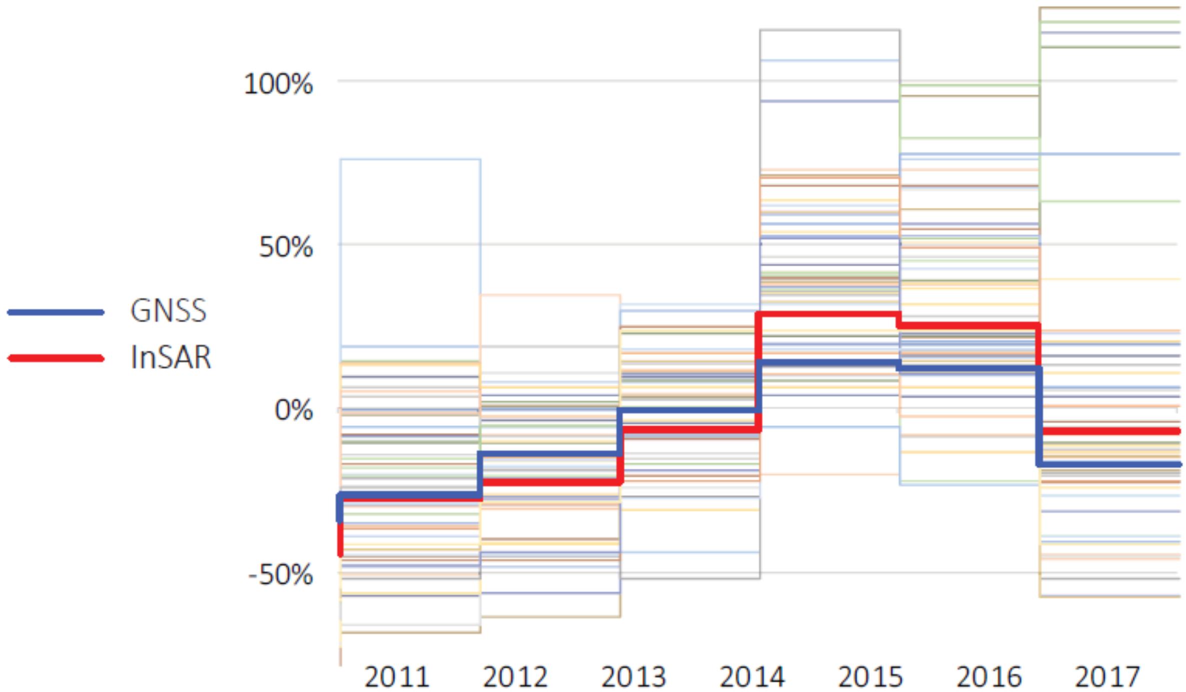

Figure 7: Relative changes of the rock glacier (summer) velocities between 2011 and 2017. The red bold line shows the average velocity change estimated based on a visual interpretation of wrapped interferograms over 6o rock glaciers. The blue bold line shows the average velocity change based on 4 permanent GNSS stations (Barboux et al., 2019).

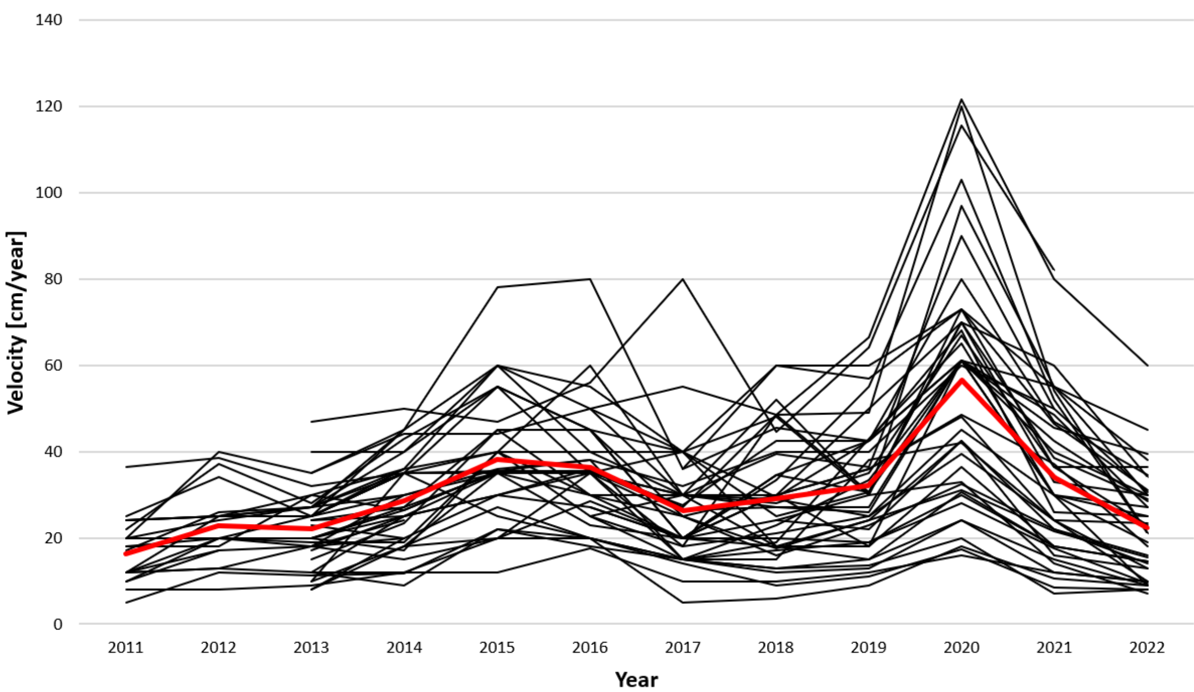

Figure 8: Rock glacier (summer) LoS velocity time series using 2011–2022 InSAR data (extension of Figure 7, with 2018–2022 data). The velocity is estimated based on a visual interpretation of wrapped interferograms over 44 rock glaciers. This is the follow-up study of Barboux et al (2019), for which the time series have been completed with the 2018–2022 time period.

3 Future work on product refinement, intercomparison and publication

3.1 Rock glacier inventory (RoGI)

The mutli-operator exercise has been completed but work remains to systematically analysis, interpret and publish the results. Between November 2023 and January 2024, each PI will summarise their main findings in a short report to be included in the PVIR. In parallel, the UNIFR team will perform a systematic verification of the delivered results to correct technical errors and formal mistakes in describing the file attributes. After these last corrections, the geopackages files containing the consensus-based primary markers (incl. morpho-kinematics attributes), the InSAR-based moving areas and the rock glacier outlines will be considered as final. The data properties will be described in the PUG and the analysis of differences between individual solutions from operators and final consensus-based results will be discussed in the PVIR.

At the end of iteration 1, we aim to publish the results for all subareas, incl. a presentation of the main conclusions regarding the consensus-based process, a discussion of the discrepancies and suggestions to solve them (improvement of guidelines). An abstract to the International Conference on Permafrost (ICOP, Whitehorse, Canada, June 2024) is about to be submitted and a manuscript will be drafted in Spring 2024. The concrete plan for publication will be discussed with all PIs. The RoGI QGIS projects will also be released as online exercises for training the community on how to inventory rock glaciers in various environments.

In iteration 2, the results may be used as training data for RoGI using machine learning. This is planned to be performed by third parties, in synergy with an upcoming RGIK working group on the same topic. Based on the findings of the exercise, we will also encourage all partners institutions to correct their initial regional inventories (CCI Permafrost Phase 1). Identified sections of RGIK guidelines showing a lack of clarity will be adjusted based on the exercise conclusions. Based on the updated guidelines, we will evaluate the potential to generate inventories in new regions. Further support for external partners will be further discussed at the end of iteration 1.

3.2 Rock glacier velocity (RGV)

During iteration 1, the RGV component remained at a pilot stage, with a focus on consolidating the baseline principles to monitor rock glaciers. As the decision of including RGV as ECV product is recent [AD-3], the requirements and guidelines for generating such products were still at an embryonic stage at the beginning of CCI Permafrost Phase 2. One main objective was to release a first complete version of the practical guidelines for RGV generation [RD-10] and to set the theoretical basis for using RGV as ECV product. A review paper on rock glacier velocity (Hu et al. in prep.) is about to be finalized and will likely be submitted before the end of iteration 1.

Another objective was to design an easily transferable method to automate the production of RGV by averaging unwrapped Sentinel-1 interferograms. The proposed methodology has been tested for four rock glaciers. In the PVIR, the InSAR-derived RGV pilot products at the four selected sites will be compared with GNSS-derived products. A comparison with results generated with a manual method (visualisation interpretation of wrapped interferograms) may also be discussed. In iteration 2, we aim to apply the methodology on larger number of selected landforms.

At the end of iteration 1, we will set up of working group that will collaborate on the generation and comparison of RGV over common landforms (round robin concept). The landforms will be primarily selected in Switzerland, Italy and Norway due to the focus areas of the mountain permafrost baseline, the Option 8 and the Option 9. We will also ask the PIs of the multi-operators exercise to select landforms in their 12 areas. Several researchers from various institutions will then process RGV using different techniques according to their respective expertise (optical remote sensing, radar remote sensing and terrestrial geodetic survey). The objective is to evaluate if the RGV requirements are clear enough to provide comparable products and to discuss where/when one technique may be more/less appropriate than another. A workshop is planned in Fall 2024, in synergy with RGIK activities. The comparison and potential integration of time series from different methods is also in synergy with the objectives of the Option 8 (PermaSeries: Integration of complementary rock glacier velocity time series for the monitoring of mountain permafrost).

4 References

4.1 Bibliography

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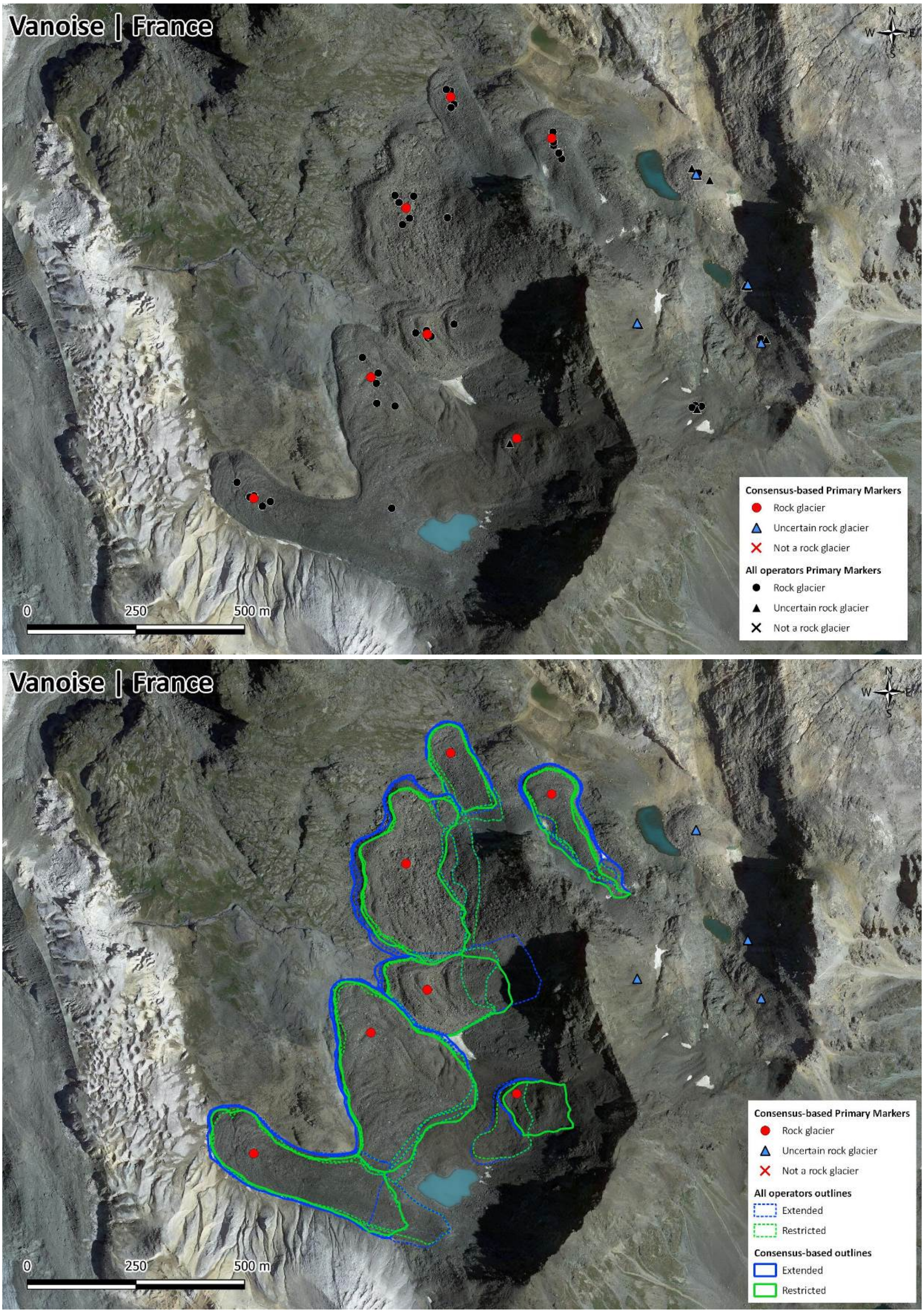
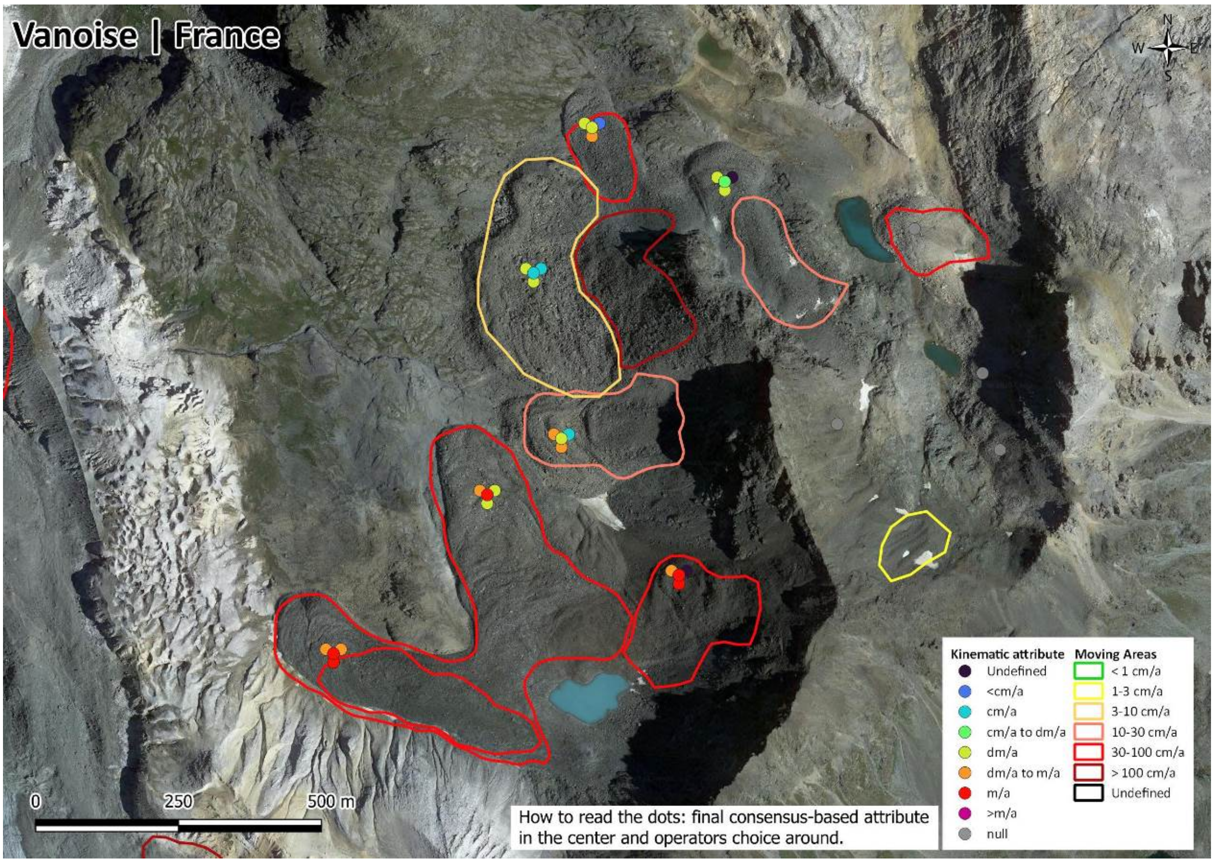
4.2 Acronyms

AD	Applicable Document
AI	Artificial Intelligence
ALT	Active Layer Thickness
ADP	Algorithm Development Plan
ATBD	Algorithm Theoretical Basis Document
BR	Breakthrough Requirement
CAR	Climate Assessment Report
CCI	Climate Change Initiative
CCN	Contract Change Notice
CRDP	Climate Research Data Package
DEM	Digital Elevation Model
E3UB	End-to-End ECV Uncertainty Budget
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GNSS	Global Navigation Satellite System

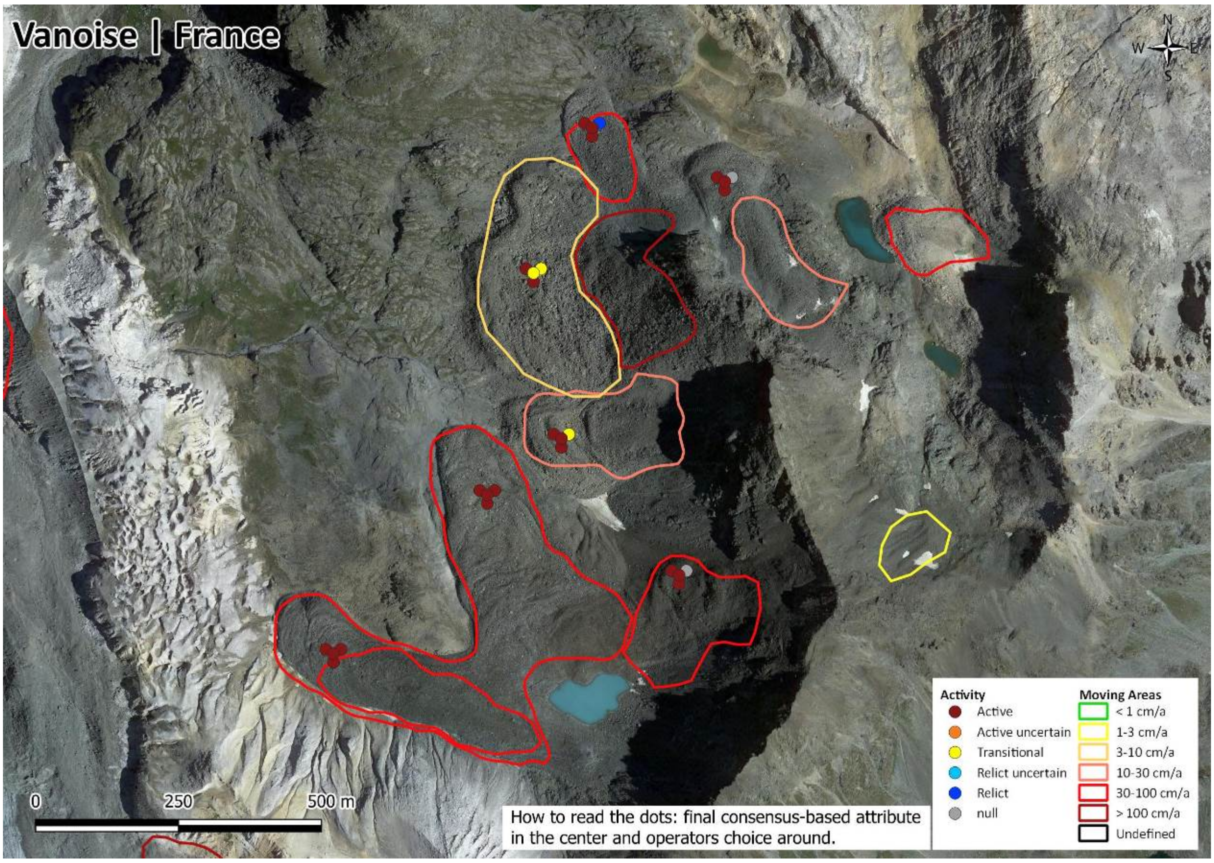
GR	Goal Requirement
GT	Ground Temperature
GTN-P	Global Climate Observing System
GTOS	Global Terrestrial Observing System
IANIGLA	Instituto Argentino de Nivología, Glaciología y Ciencias Ambientale
InSAR	Interferometric Synthetic Aperture Radar
IPA	International Permafrost Association
KA	Kinematic Attribute
LOS	Line-of-sight
MA	Moving Area
MAGT	Mean Annual Ground Temperature
MAGT	Mean Annual Ground Surface Temperature
NORCE	Norwegian Research Centre AS
PERMOS	Swiss Permafrost Monitoring Network
PI	Principal Investigator
PM	Primary Marker
PSD	Product Specification Document
PUG	Product User Guide
PVASR	Product Validation and Algorithm Selection Report
PVIR	Product Validation and Intercomparison Report
PVP	Product Validation Plan
RD	Reference Document
RG	Rock Glacier
RGIK	Rock Glacier Inventories and Kinematics
RGU	Rock Glacier Unit
RGV	Rock Glacier Velocity
RoGI	Rock Glacier Inventory
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
UiO	University of Oslo
UNIFR	University of Fribourg
URD	Users Requirement Document
URq	User Requirement
UTM	Universal Transverse Mercator
TR	Threshold Requirement
WUT	West University of Timisoara
WMO	World Meteorological Organization

Annex 1: Examples of results from RoGI multi-operator exercise

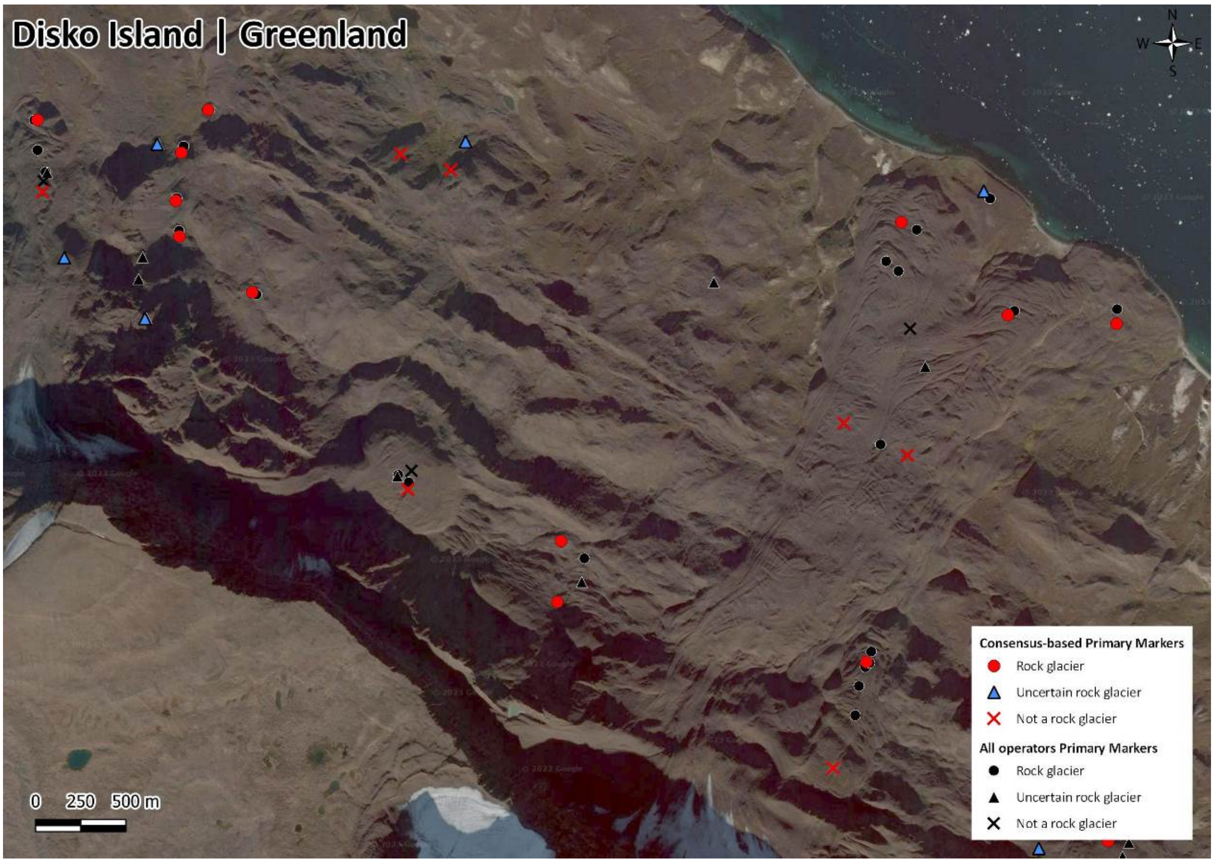


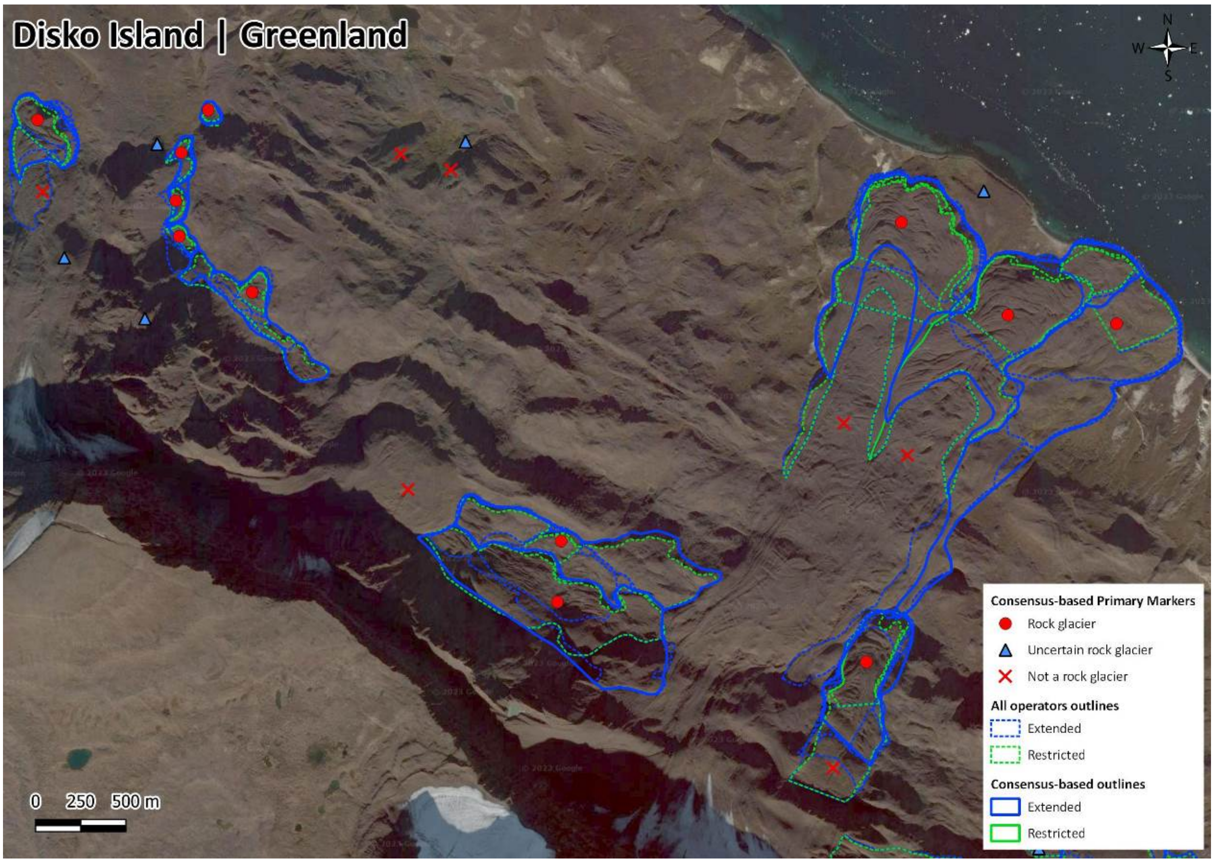


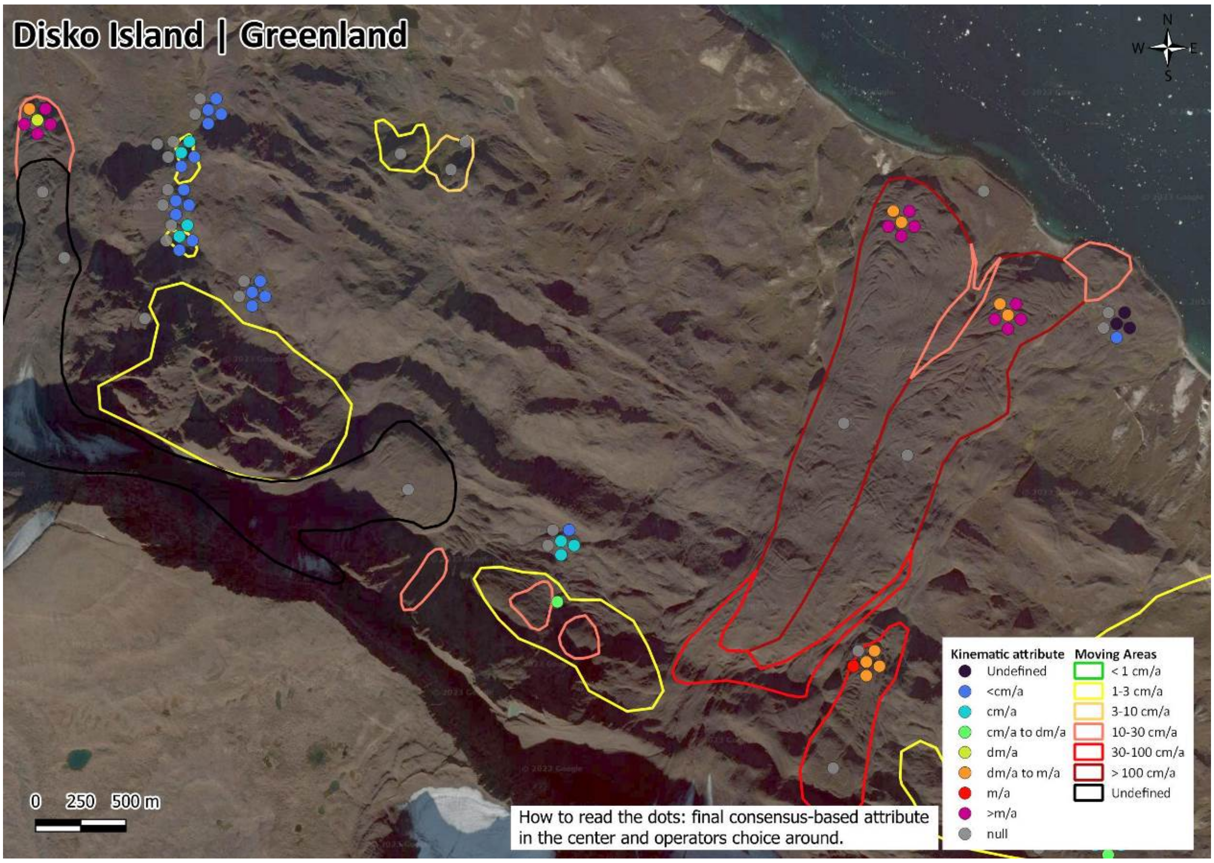
Vanoise | France
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.



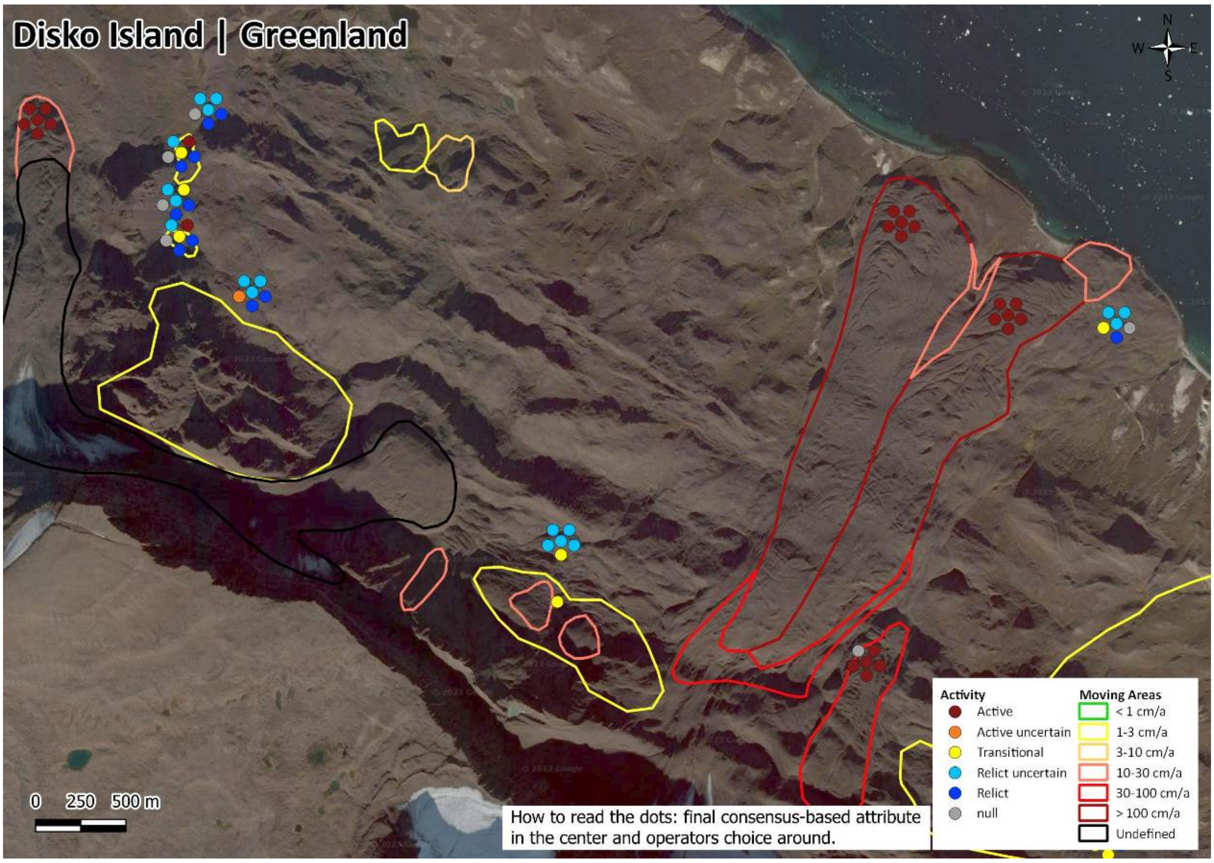
Vanoise | France
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.


Disko Island | Greenland
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
0 250 500 m

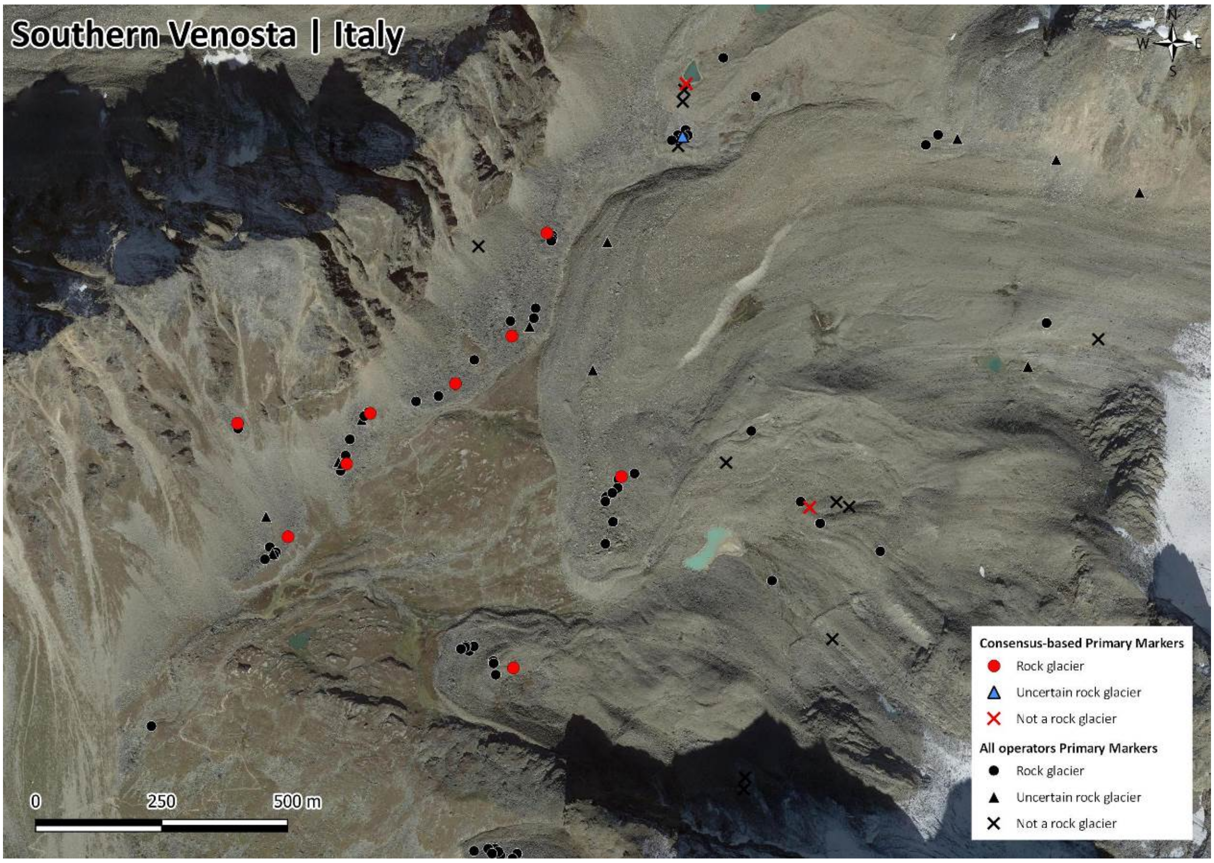

Disko Island | Greenland
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators outlines
Extended
Restricted
Consensus-based outlines
Extended
Restricted
0 250 500 m

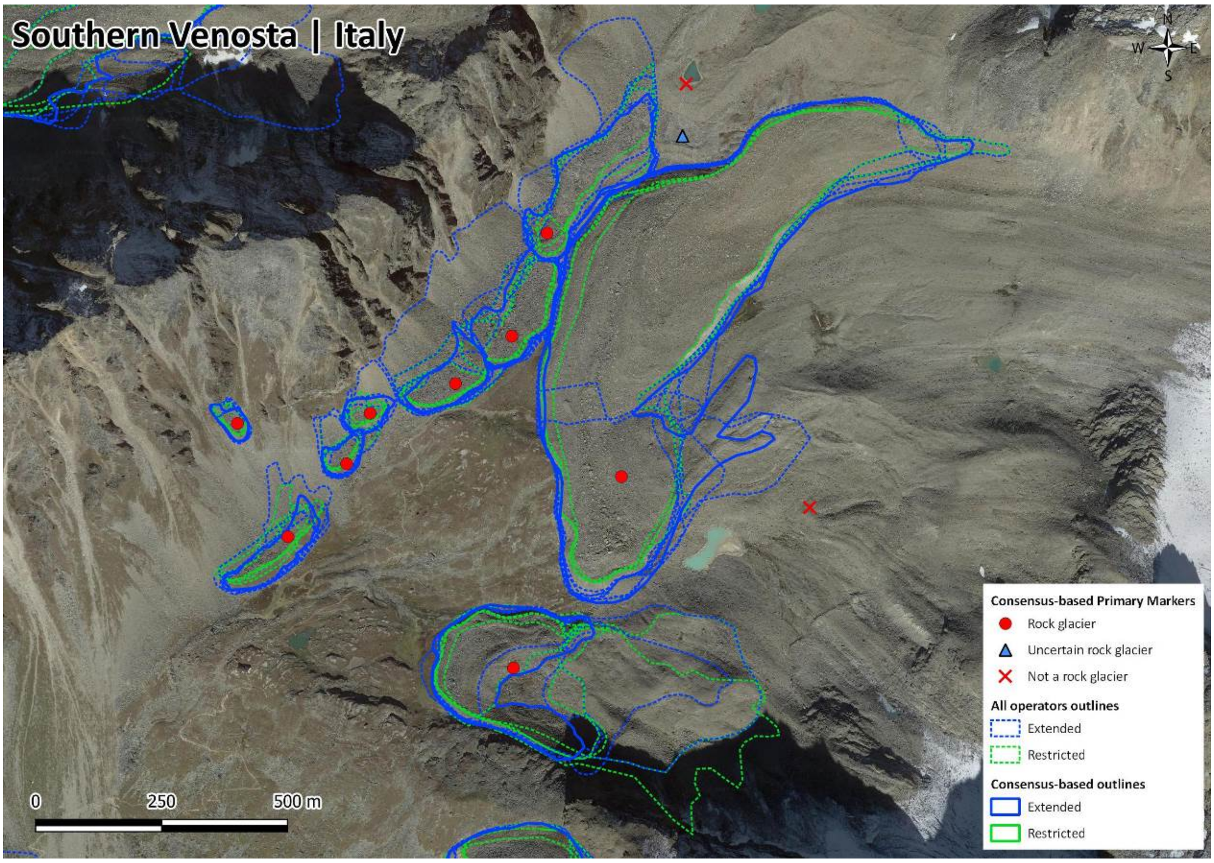


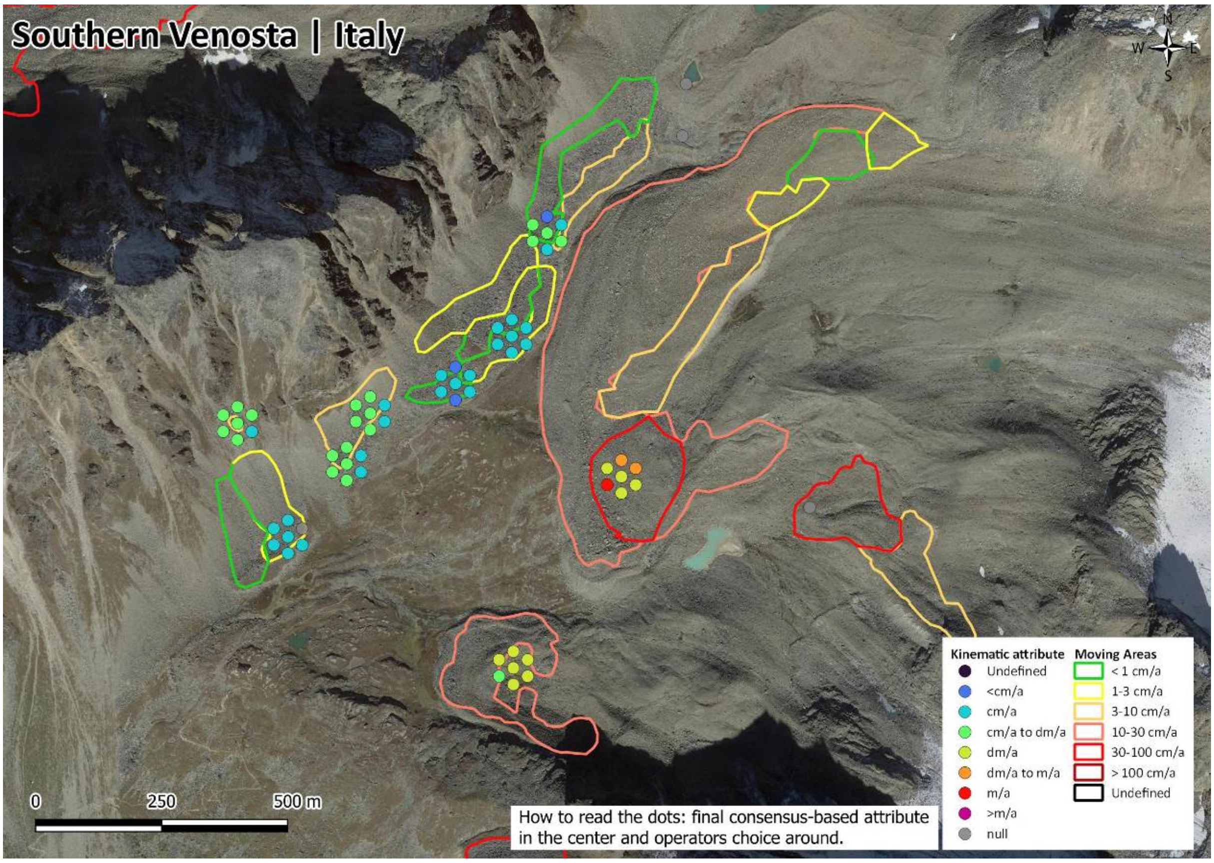
Disko Island | Greenland
N
W
E
S
0 250 500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined



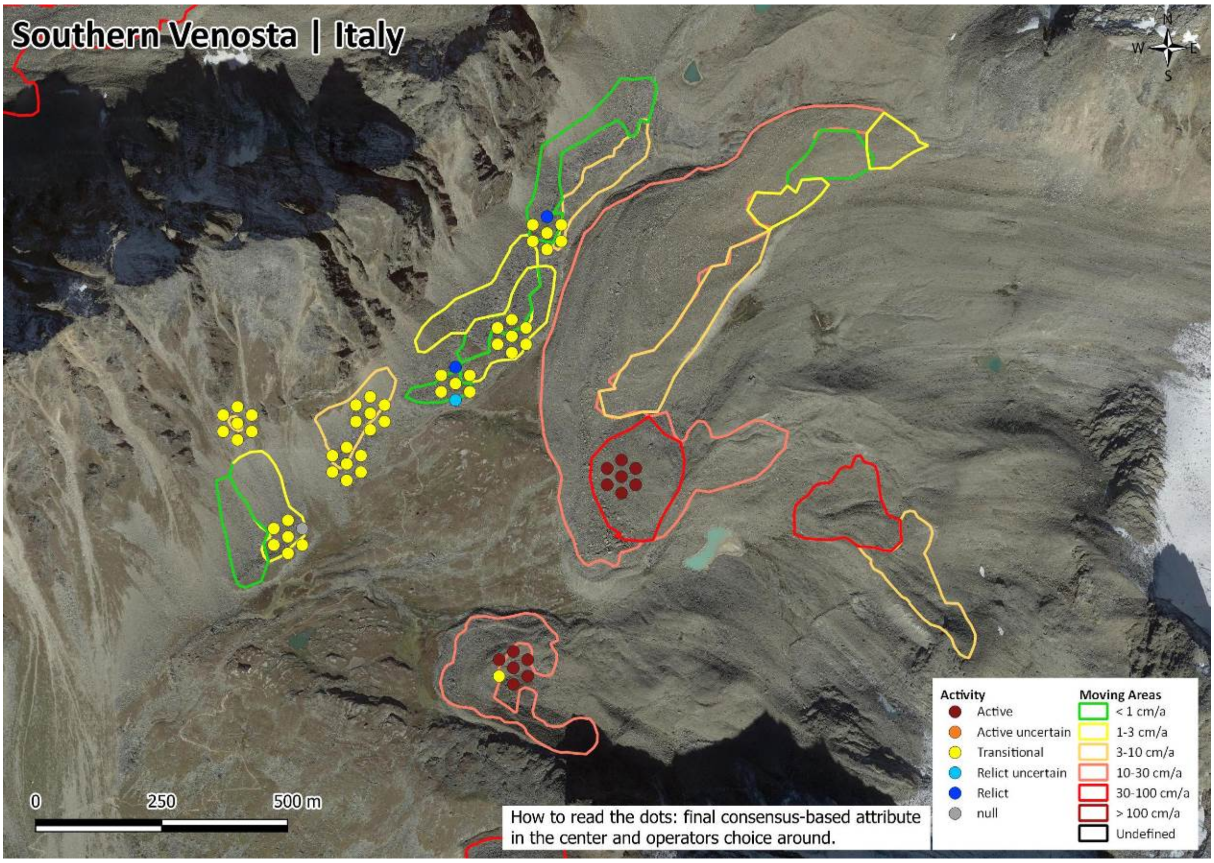
Disko Island | Greenland
N
W
E
S
0 250 500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined


Southern Venosta | Italy
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
0
250
500 m

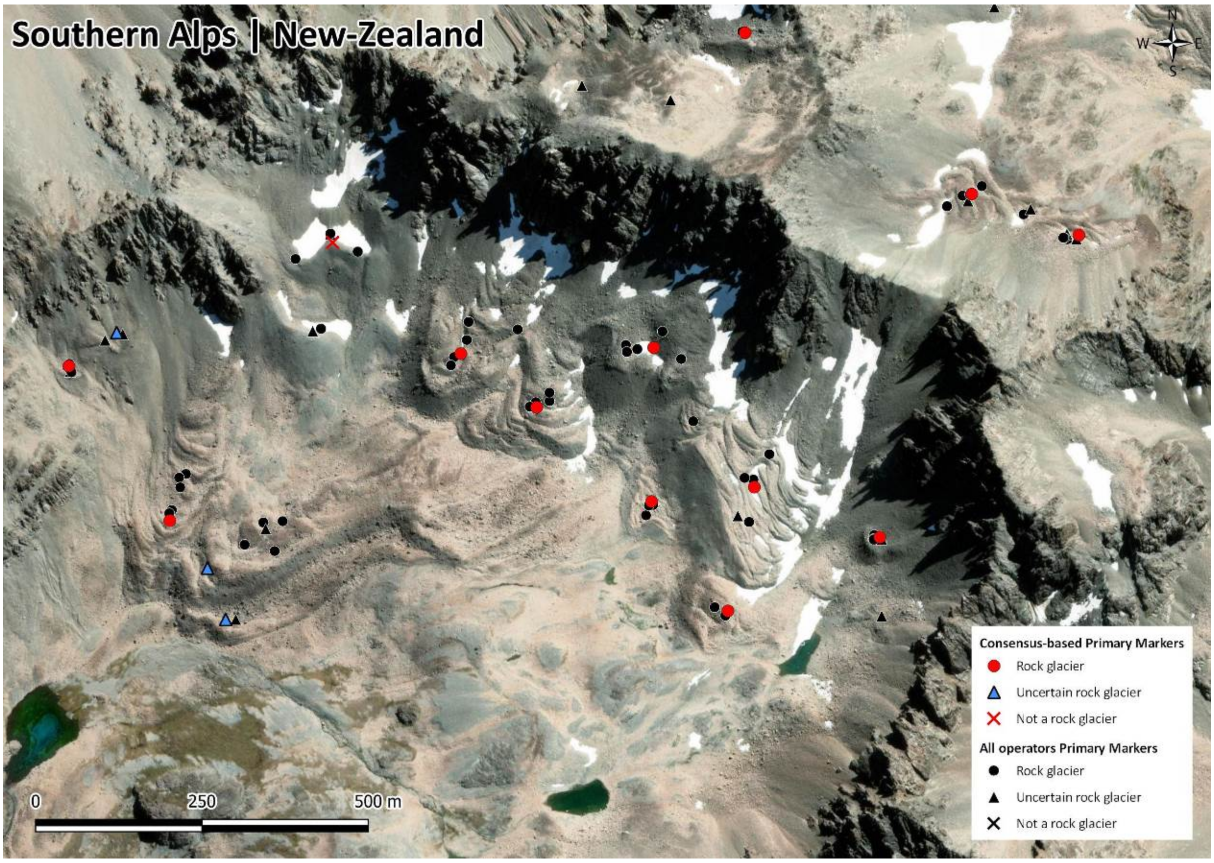

Southern Venosta | Italy
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators outlines
Extended
Restricted
Consensus-based outlines
Extended
Restricted
0
250
500 m



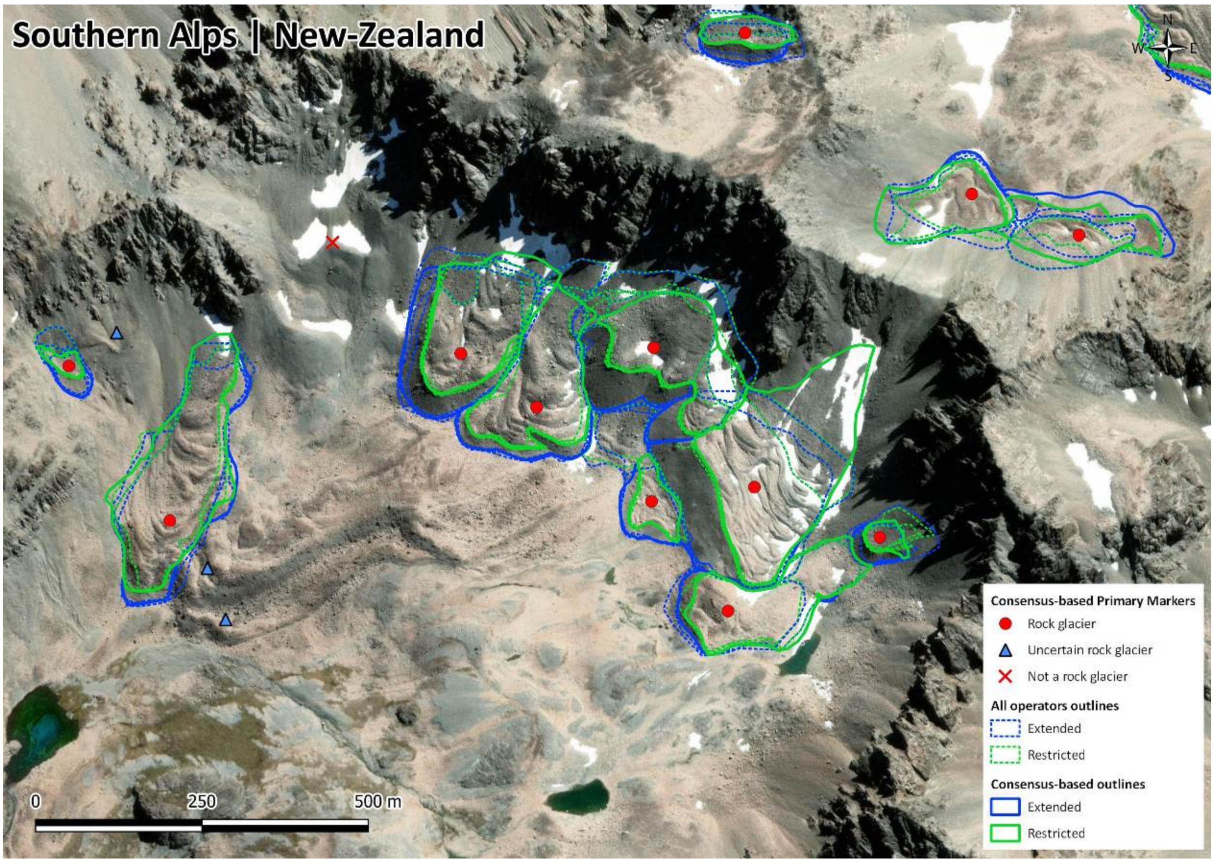
Southern Venosta | Italy
N
W
E
S
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.



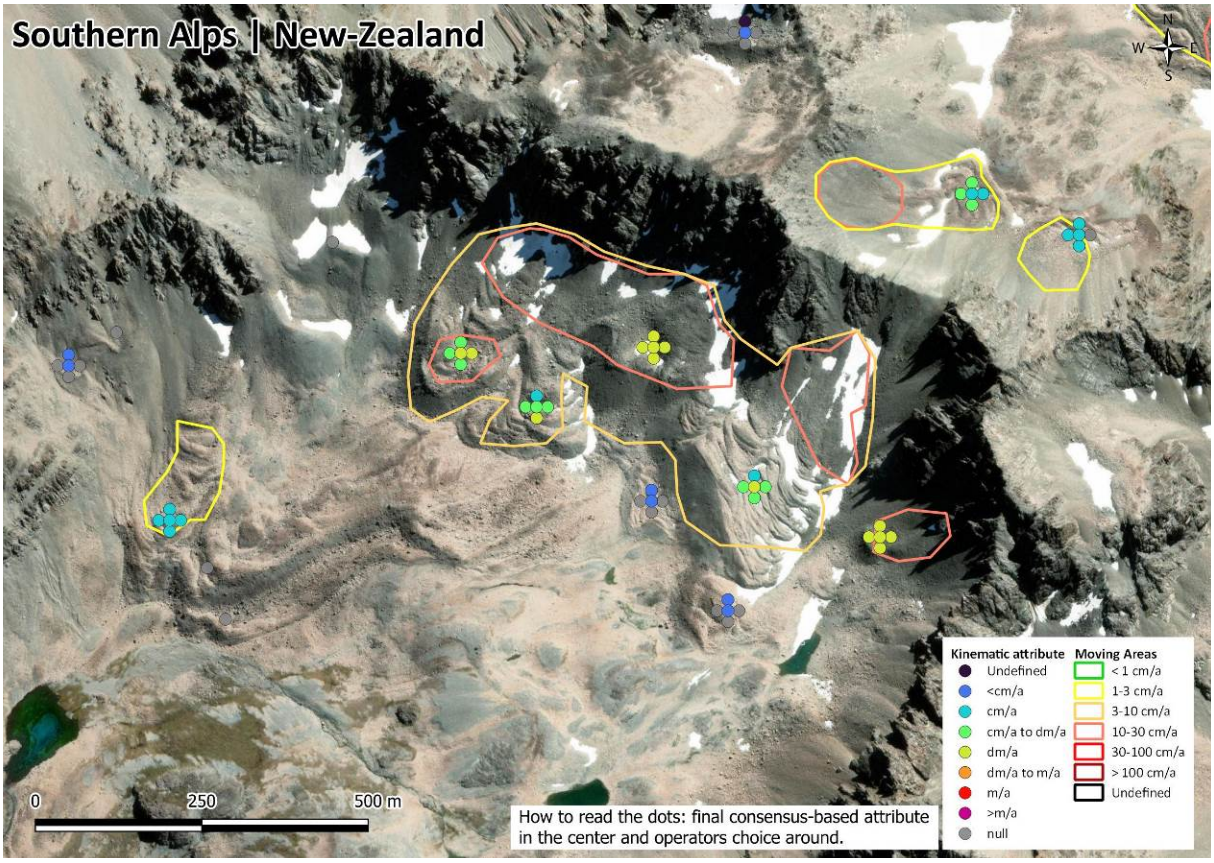
Southern Venosta | Italy
N
W
E
S
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.

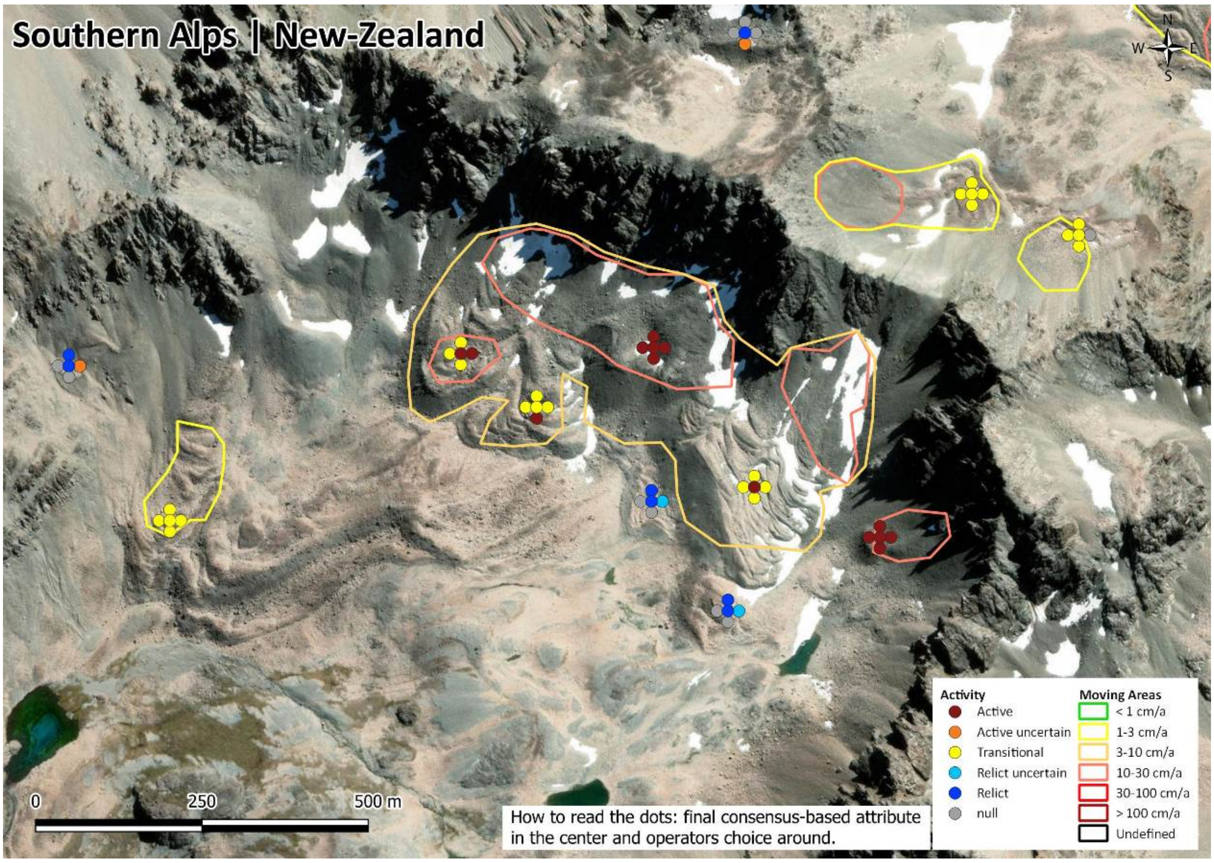


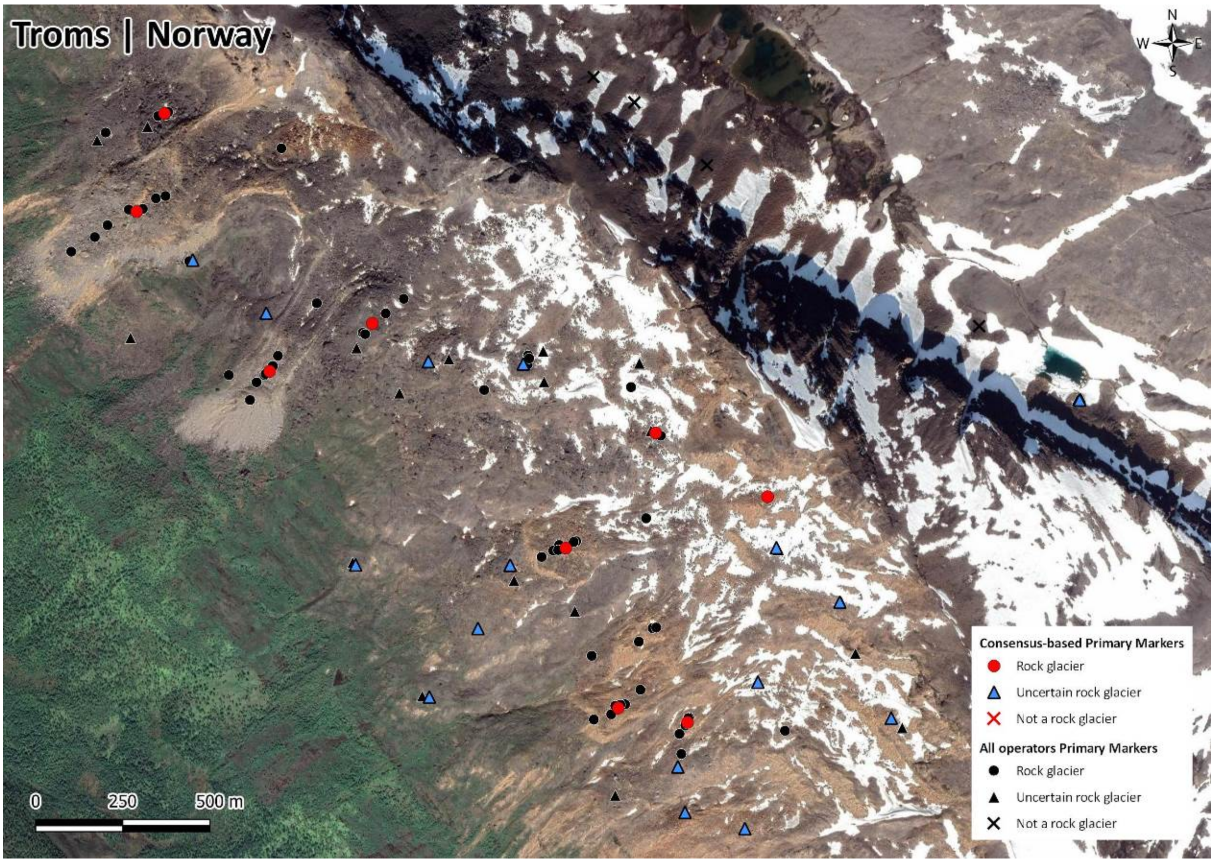
Southern Alps | New-Zealand
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
0
250
500 m

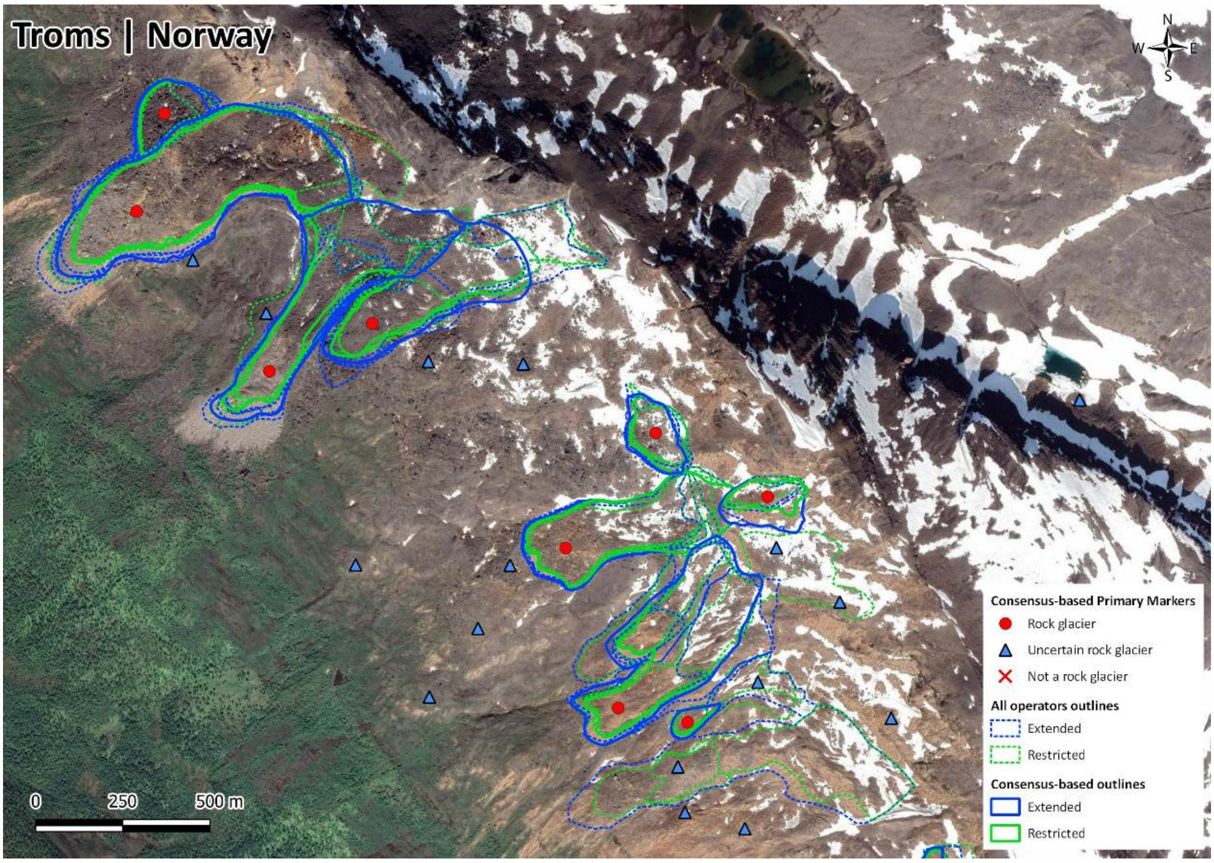


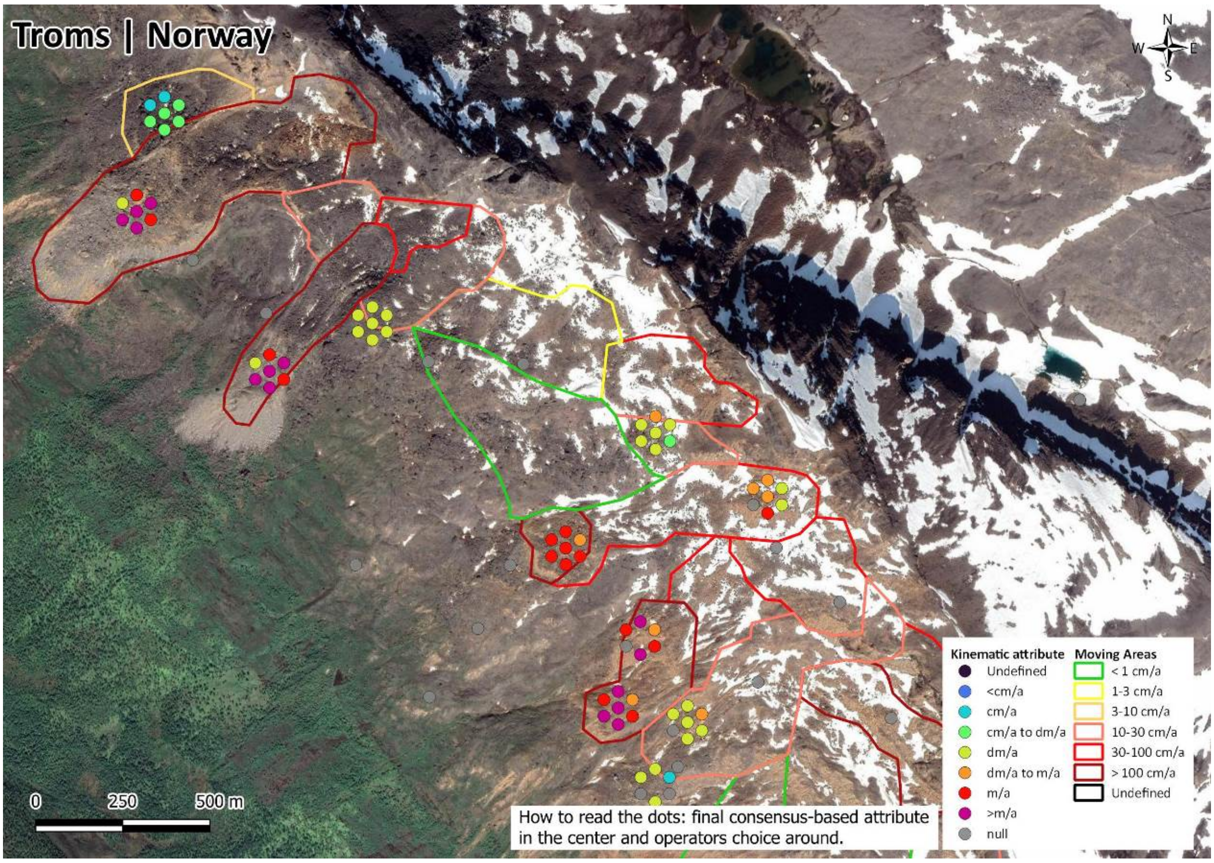
Southern Alps | New-Zealand
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators outlines
Extended
Restricted
Consensus-based outlines
Extended
Restricted
0
250
500 m


Southern Alps | New-Zealand
N
W
E
S
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.

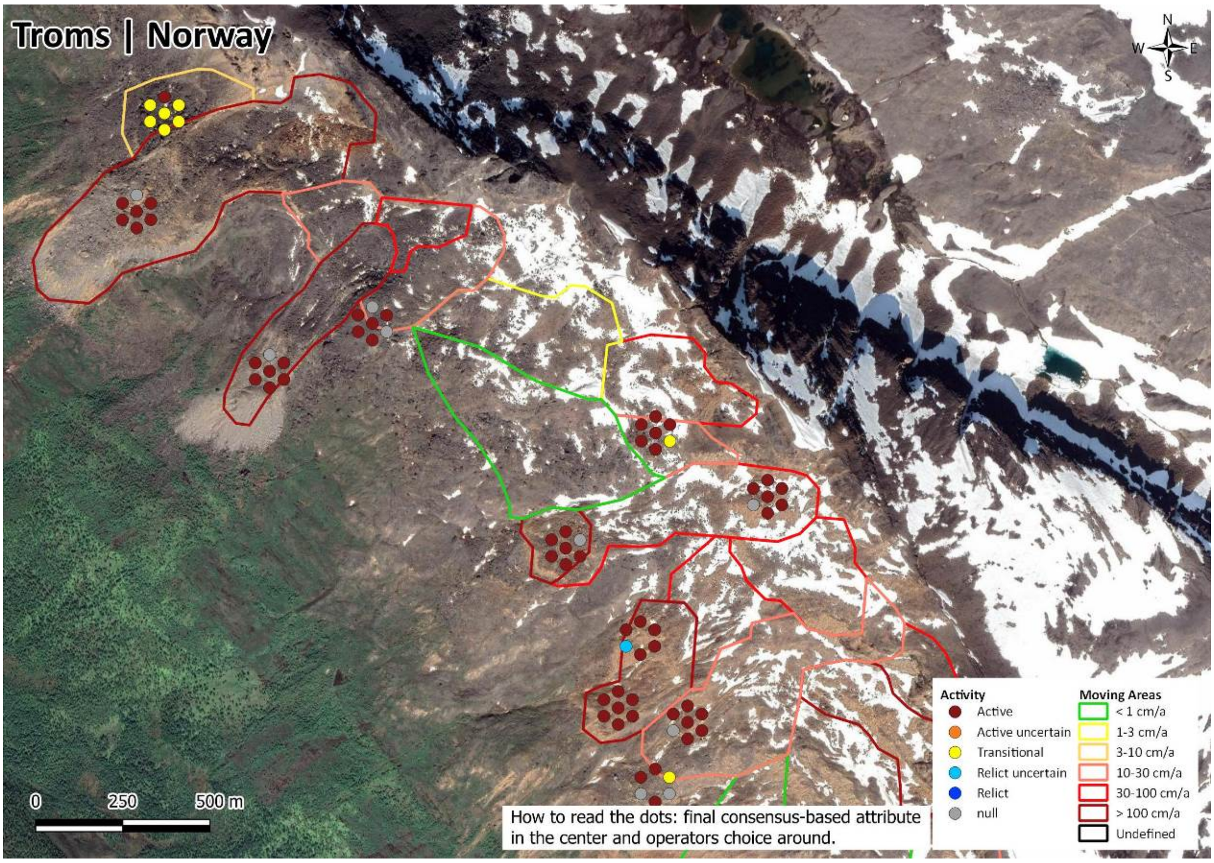

Southern Alps | New-Zealand
N
W
E
S
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.


Troms | Norway
N
W
E
S
0
250
500 m
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier

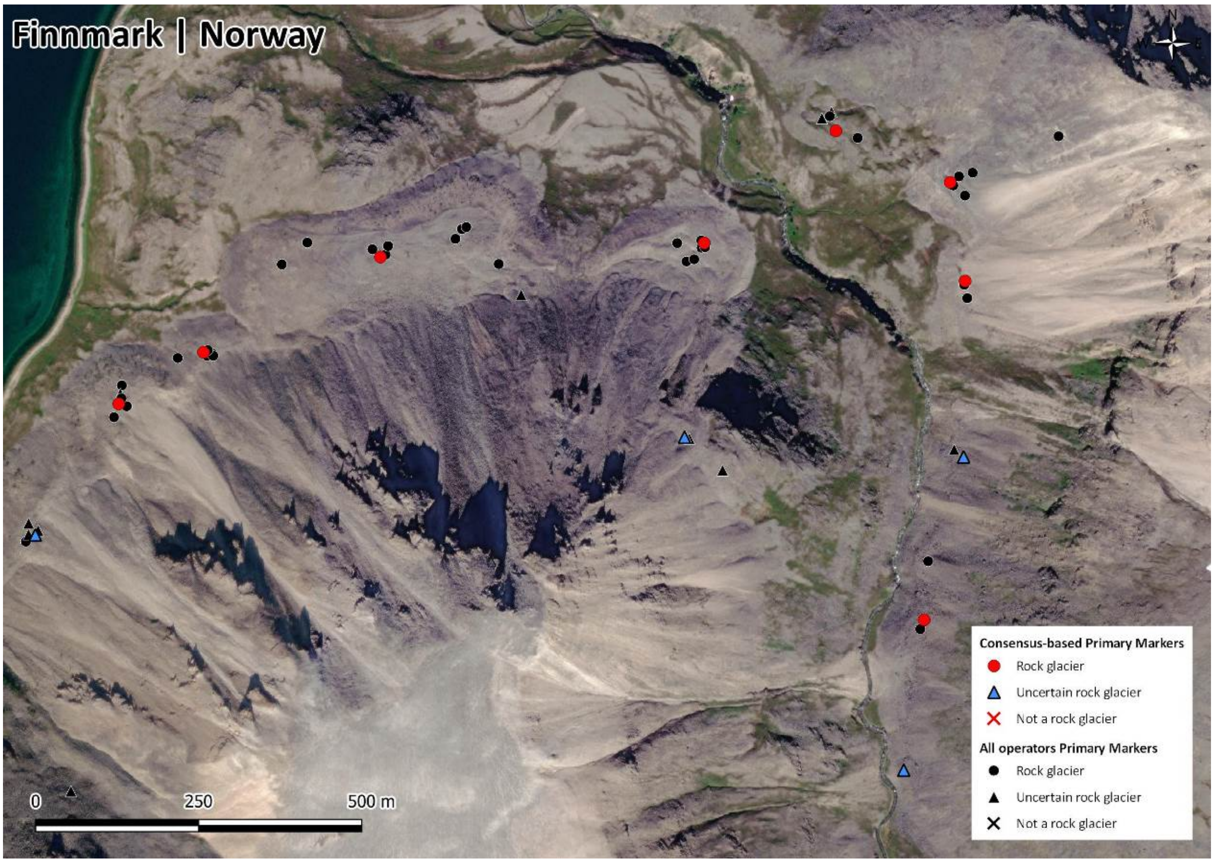

Troms | Norway
N
W
E
S
0
250
500 m
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators outlines
Extended
Restricted
Consensus-based outlines
Extended
Restricted



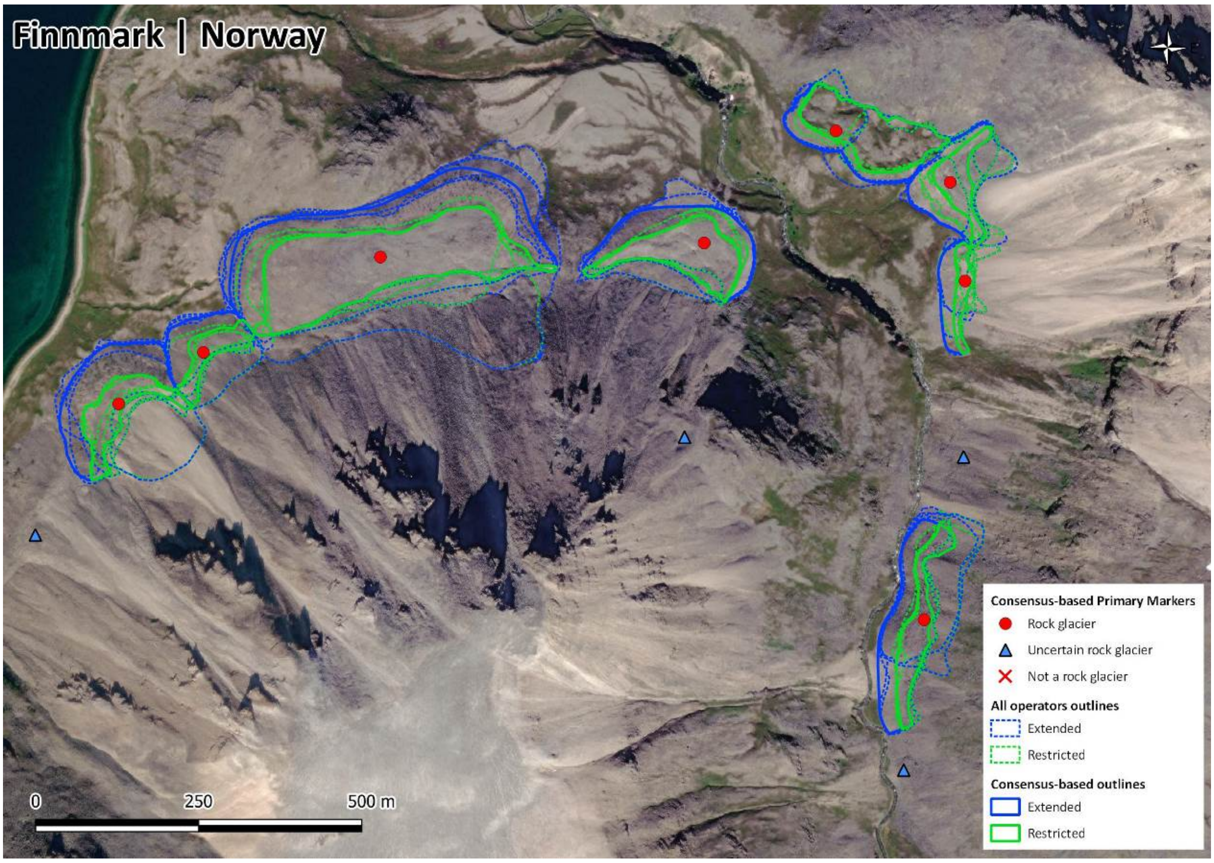
Troms | Norway
N
W
E
S
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.



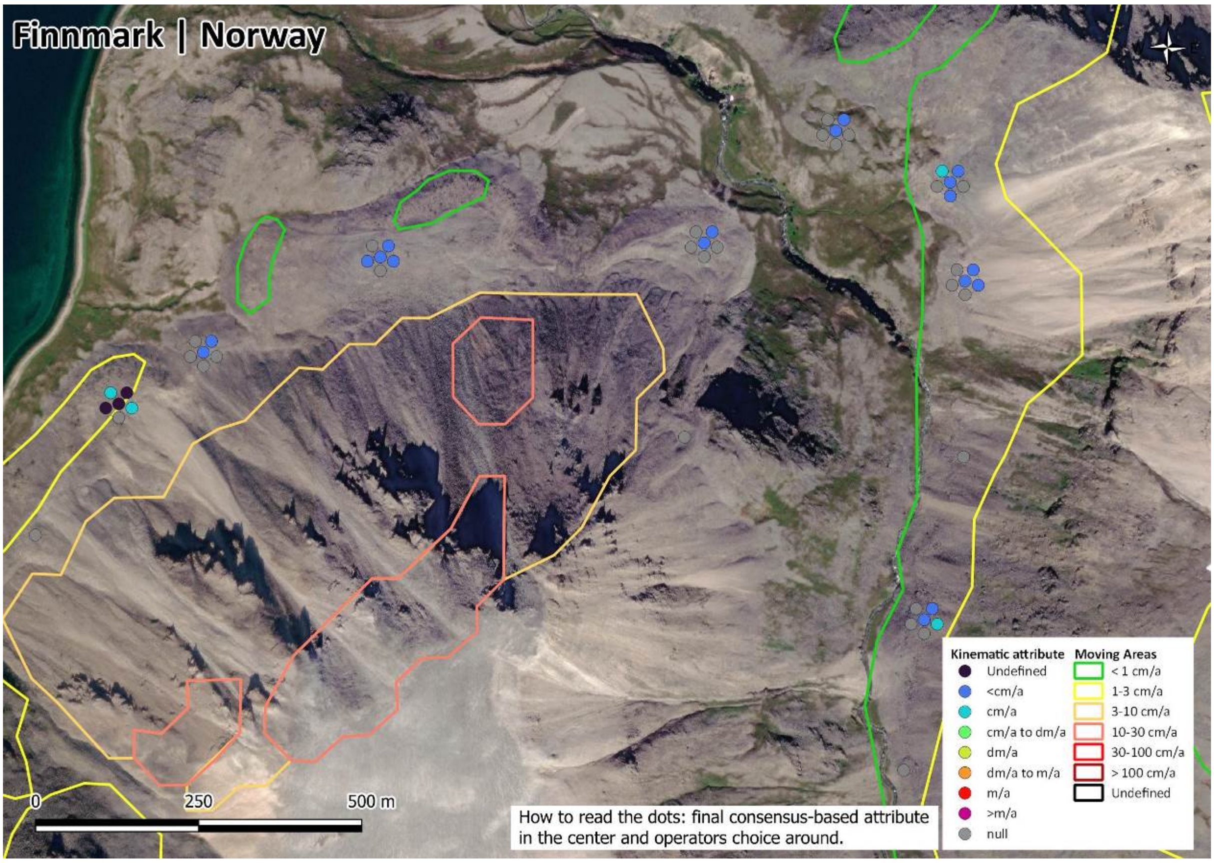
Troms | Norway
N
W
E
S
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.



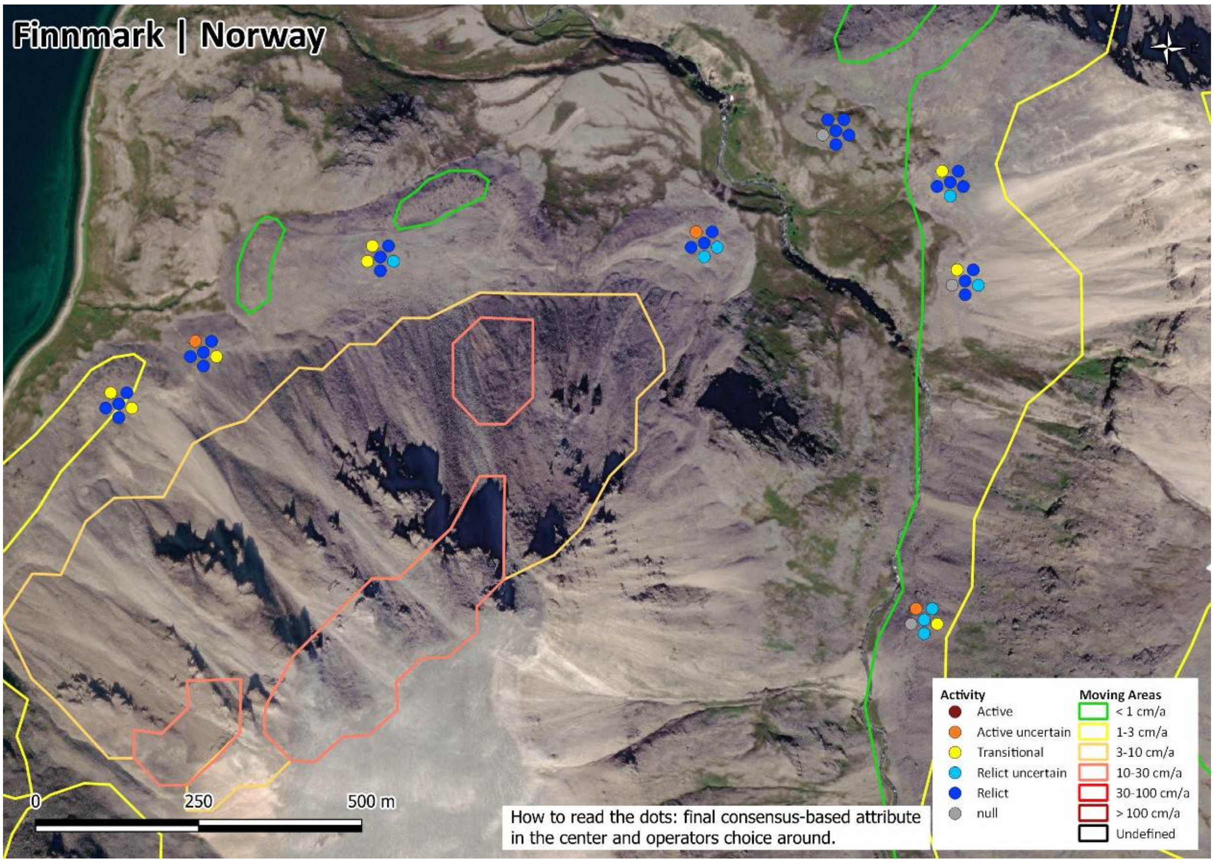
Finnmark | Norway
0
250
500 m
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier



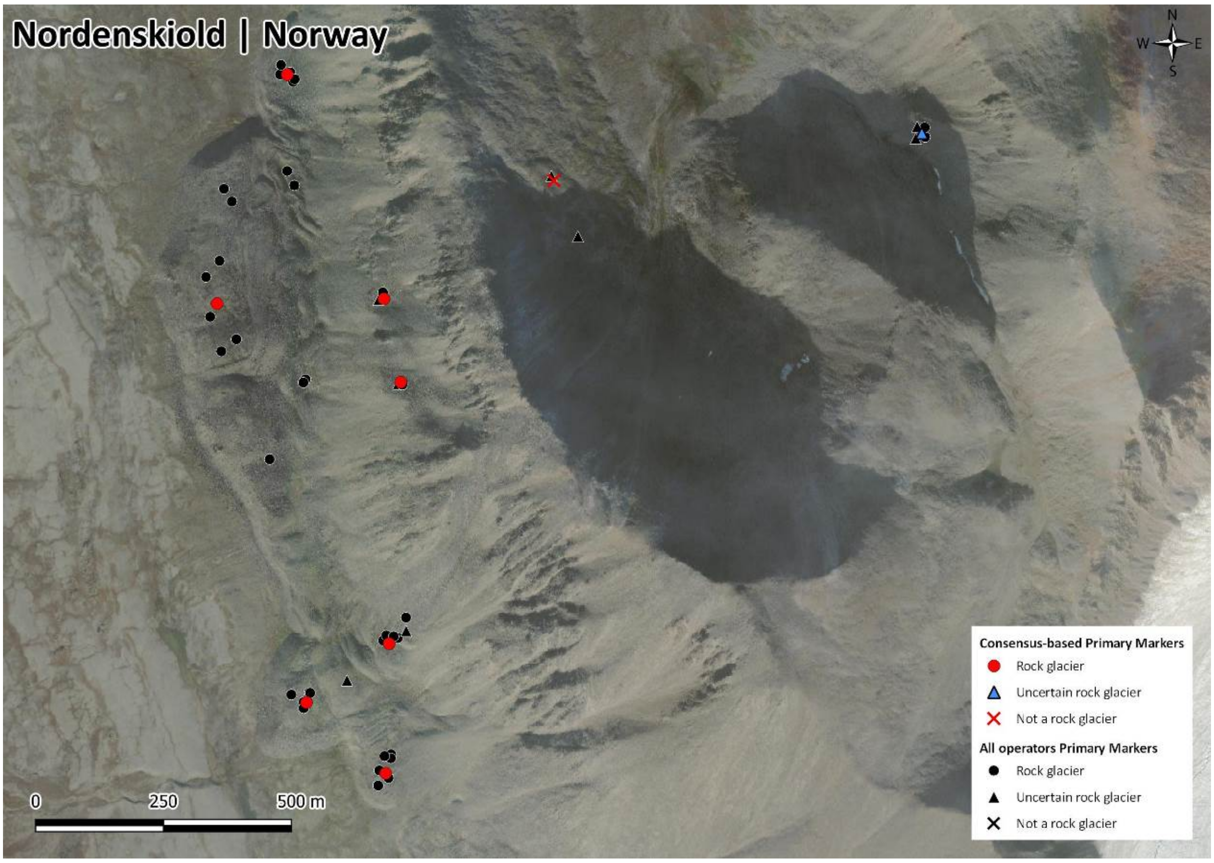
Finnmark | Norway
0
250
500 m
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators outlines
Extended
Restricted
Consensus-based outlines
Extended
Restricted



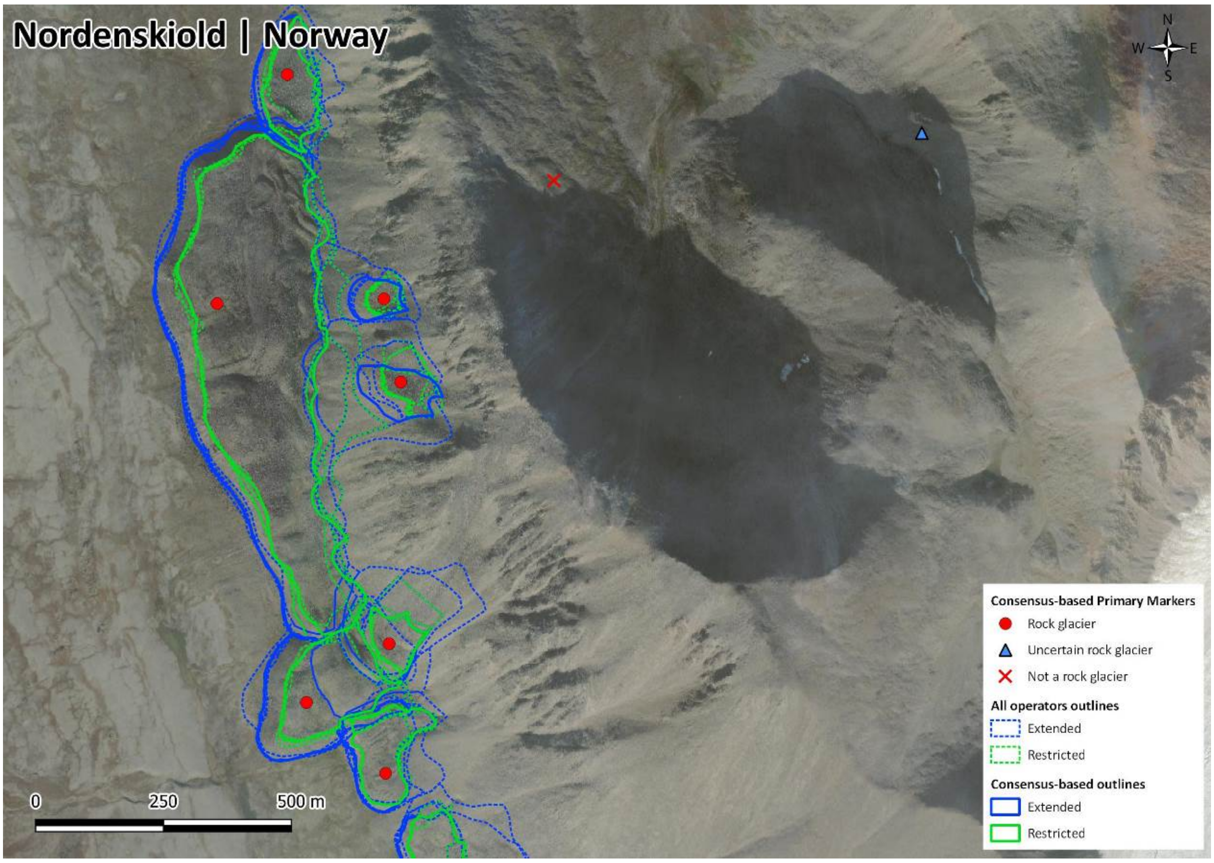
Finnmark | Norway
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.



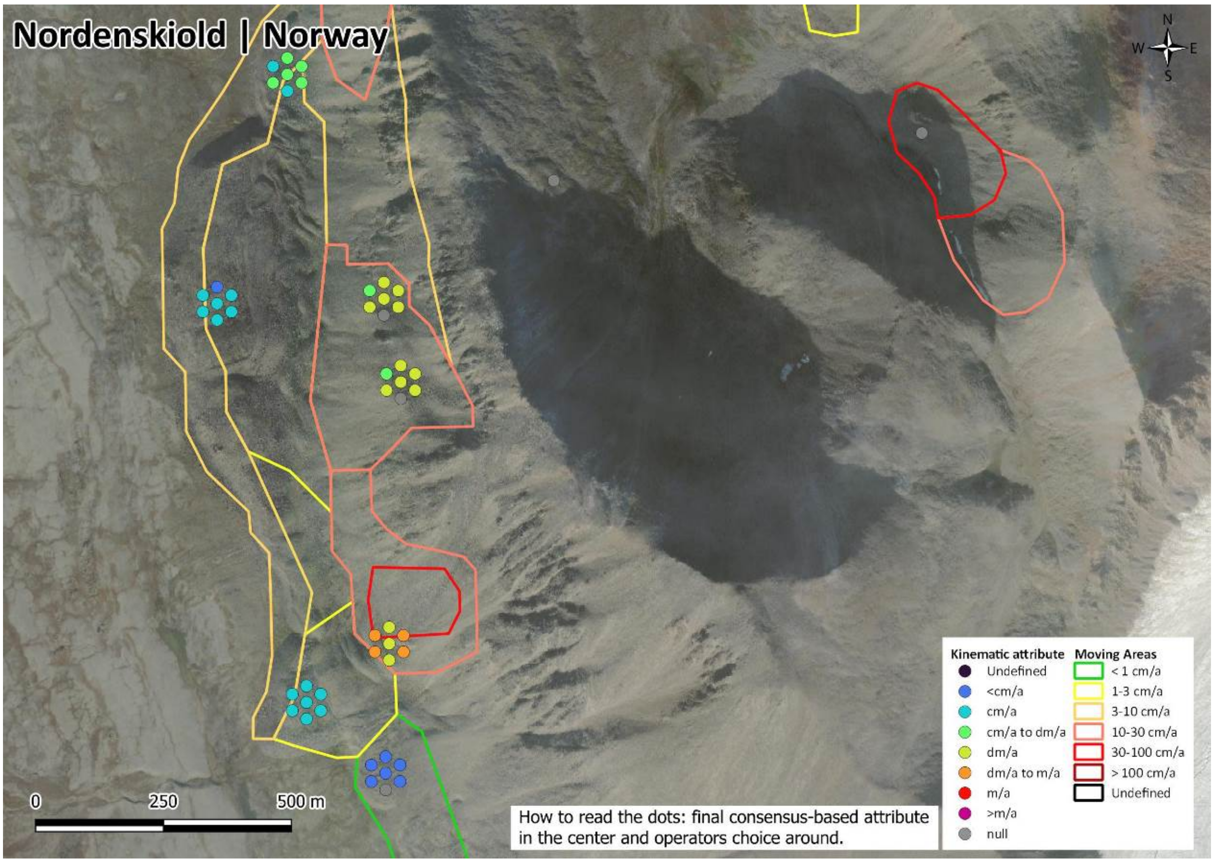
Finnmark | Norway
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.

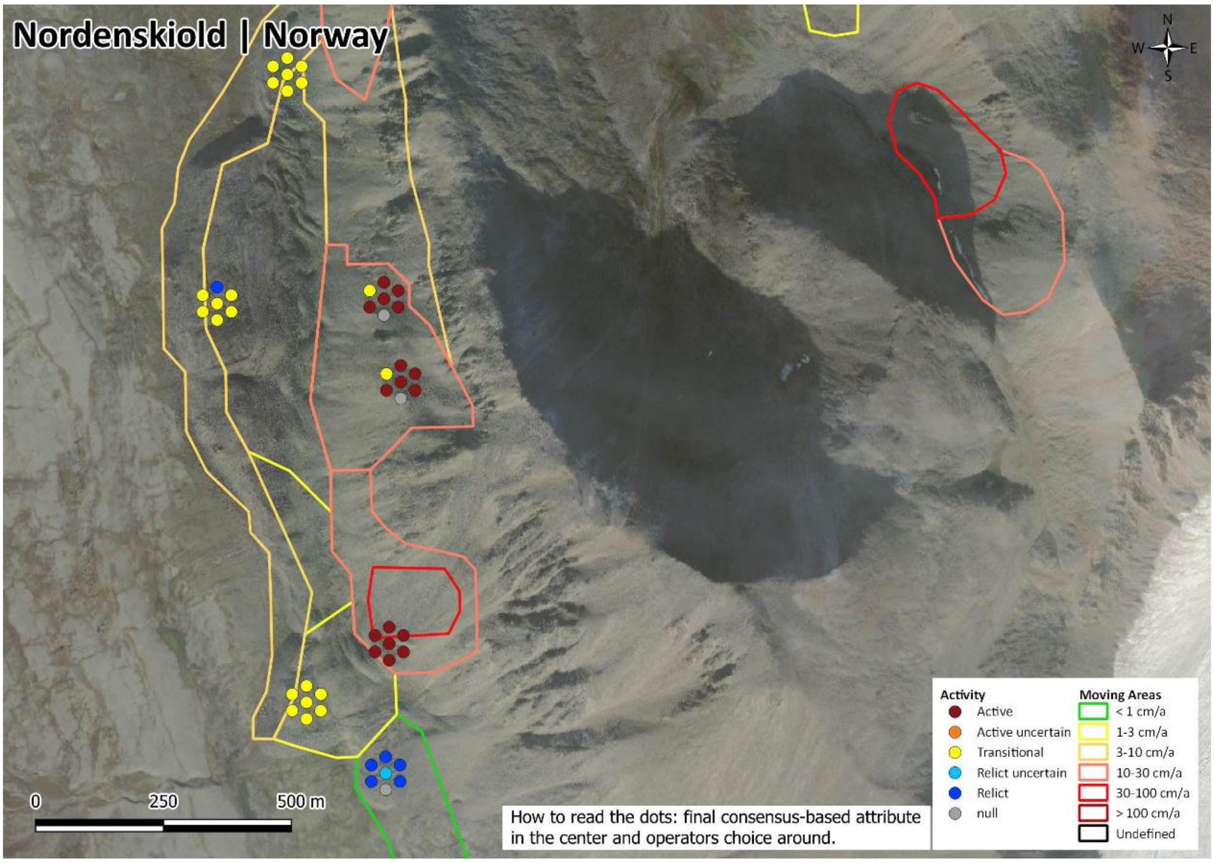


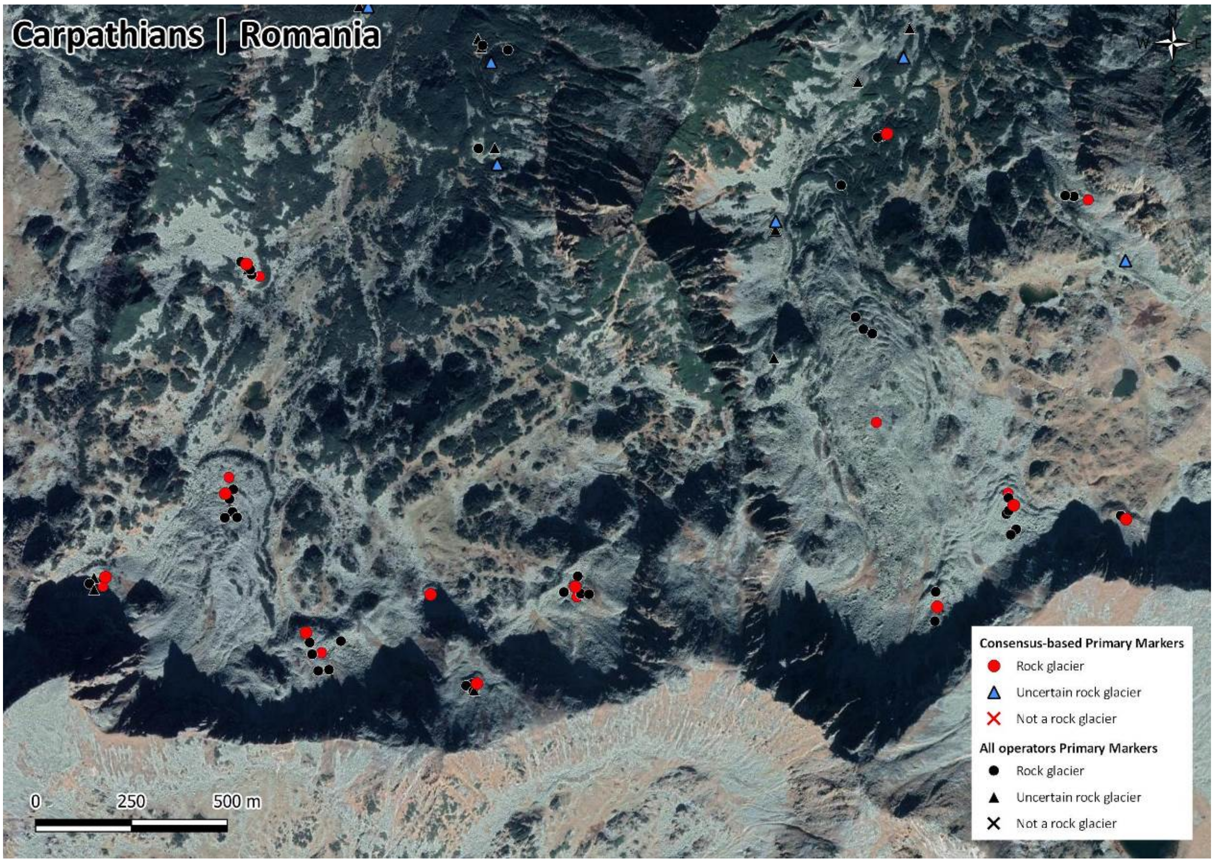
Nordenskiold | Norway
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
0
250
500 m

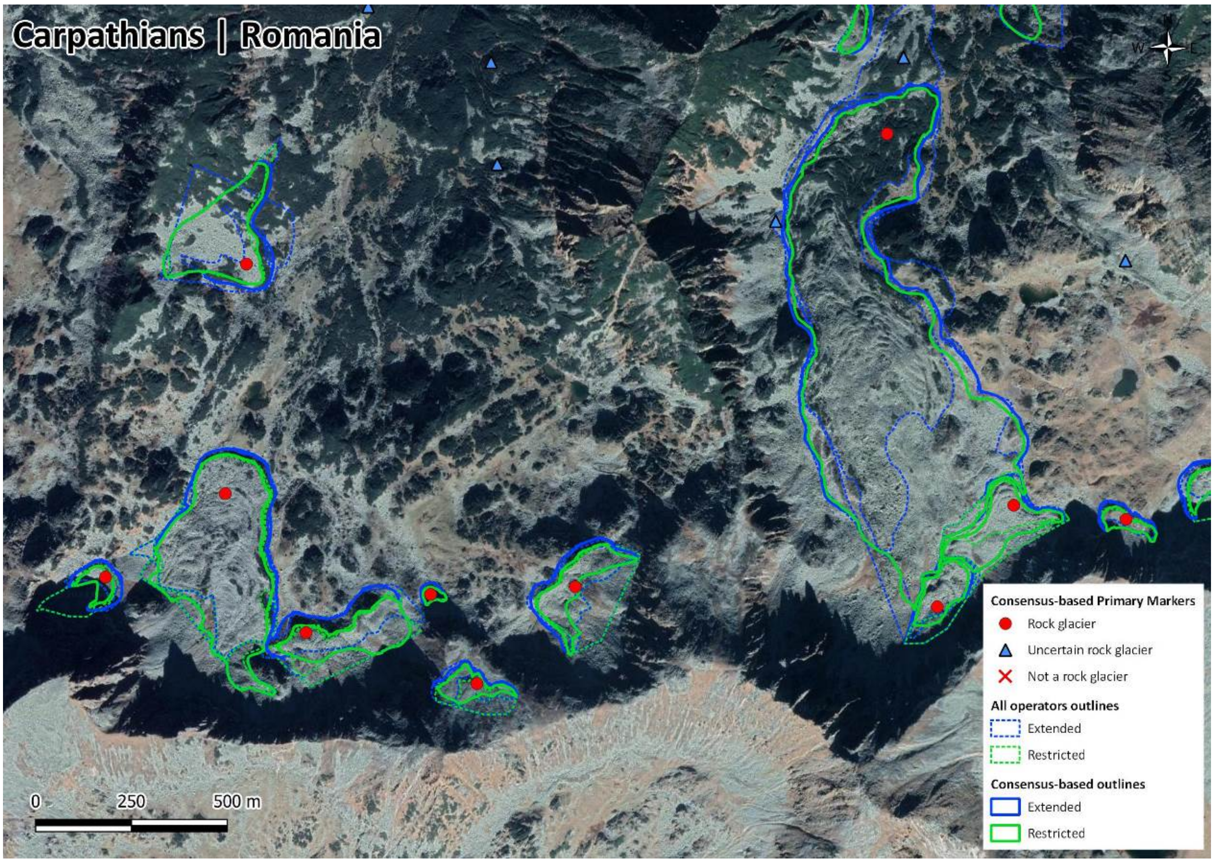


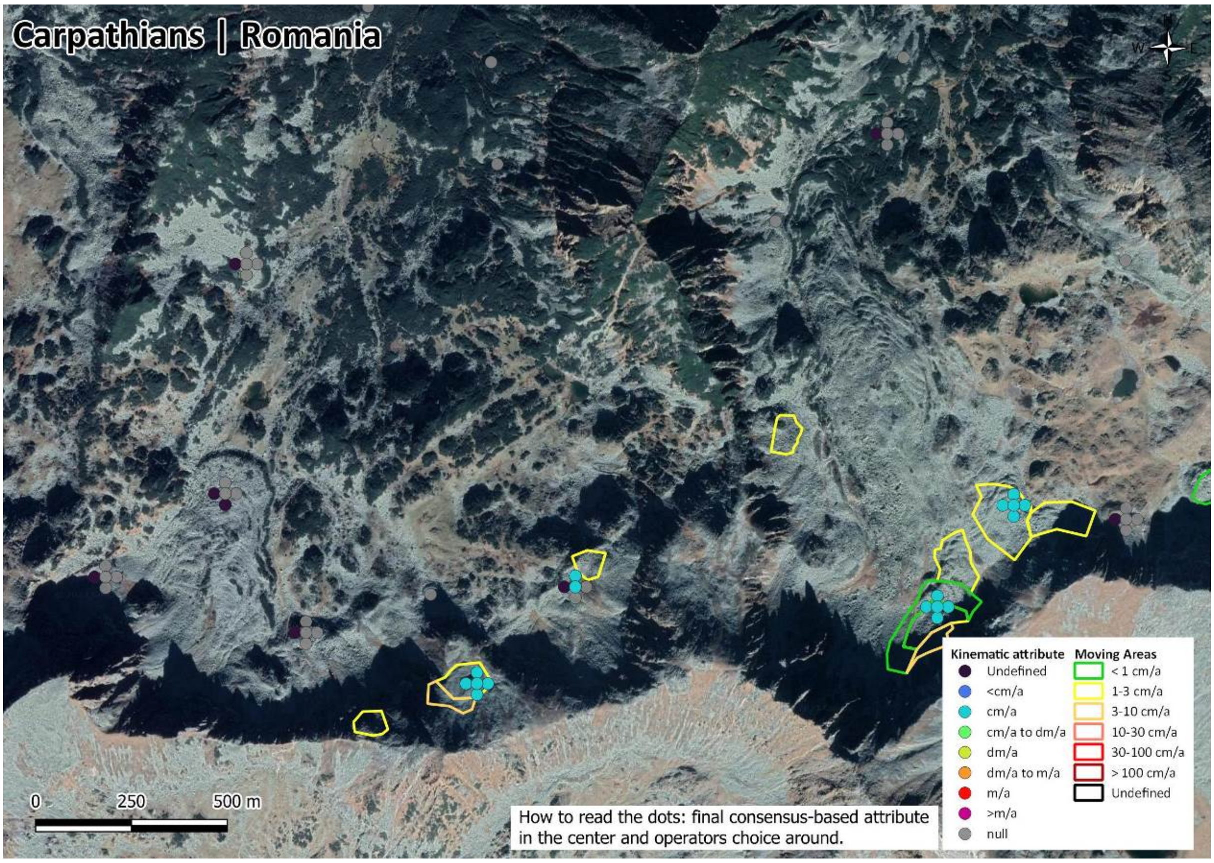
Nordenskiold | Norway
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators outlines
Extended
Restricted
Consensus-based outlines
Extended
Restricted
0
250
500 m


Nordenskiold | Norway
N
W
E
S
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined

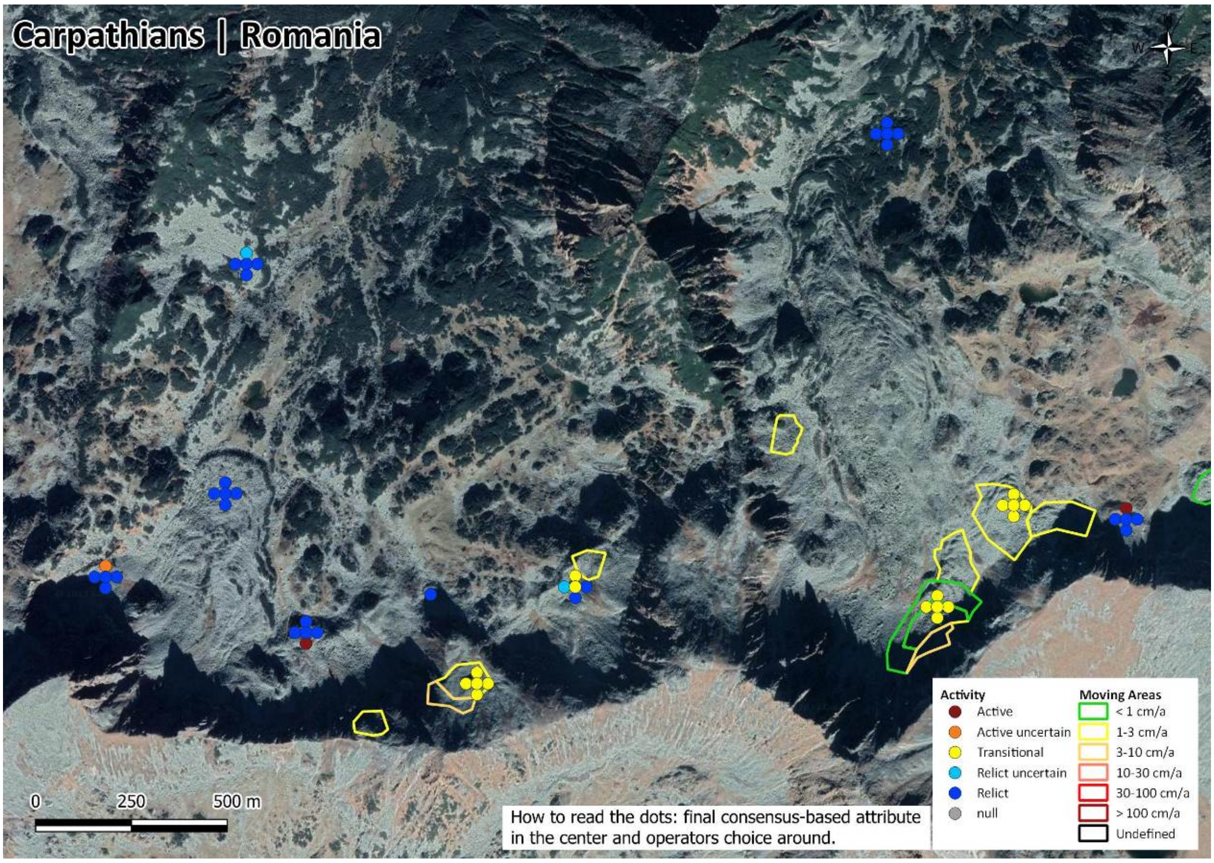

Nordenskiold | Norway
N
W
E
S
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined


Carpathians | Romania
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
0
250
500 m

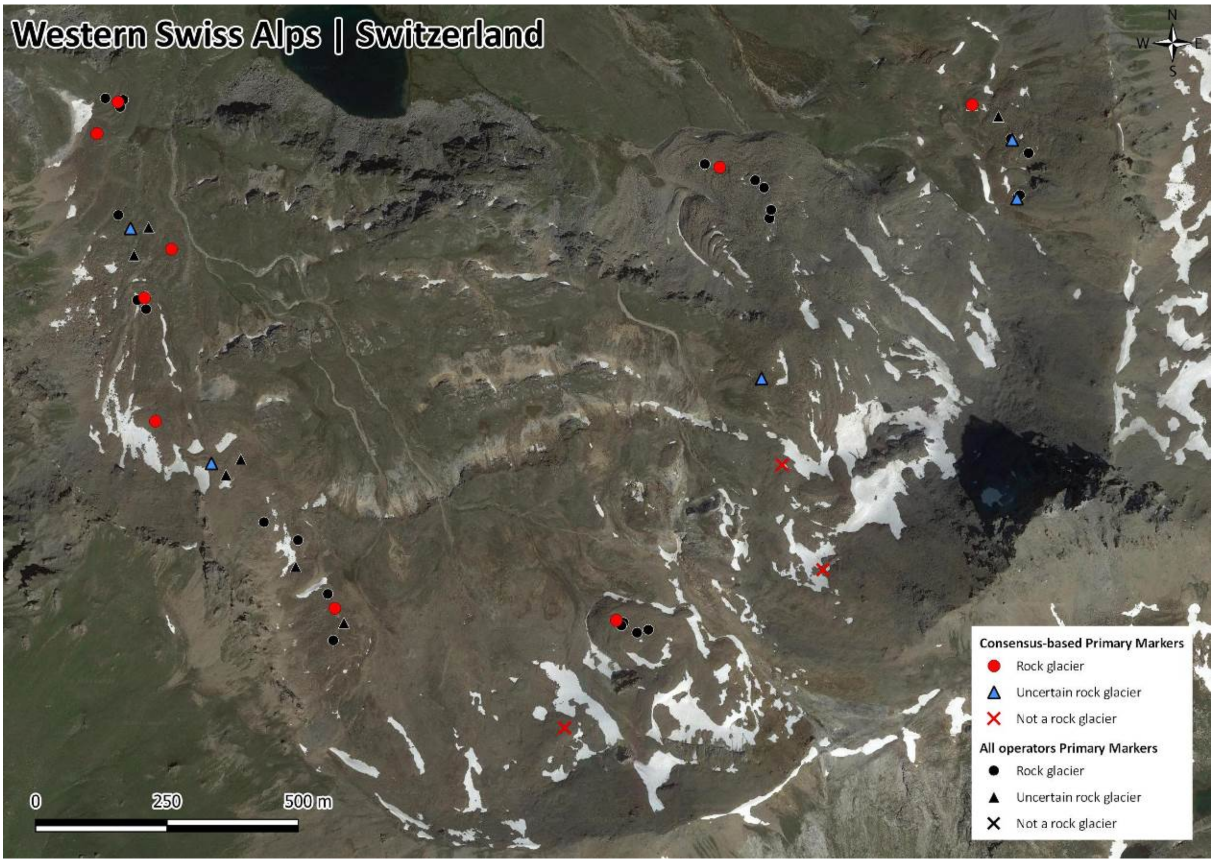

Carpathians | Romania
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators outlines
Extended
Restricted
Consensus-based outlines
Extended
Restricted
0
250
500 m

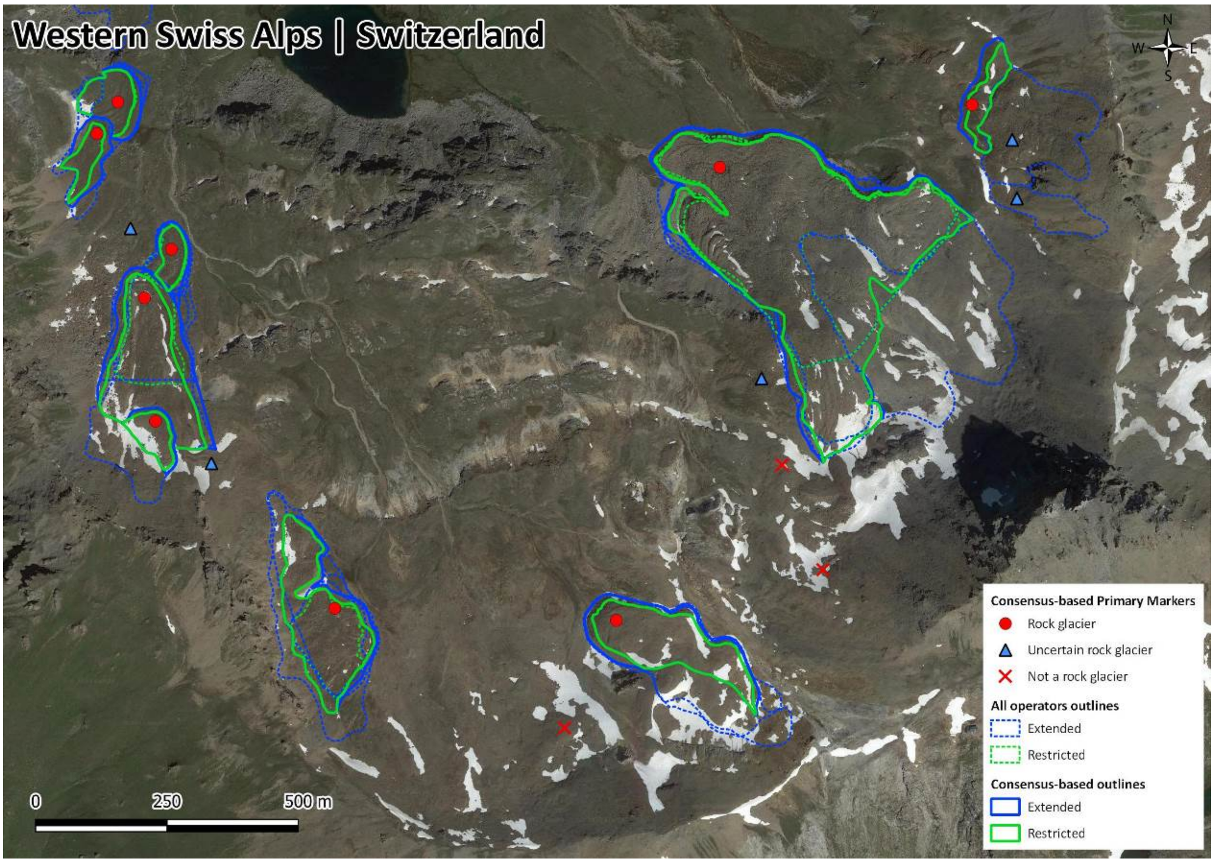


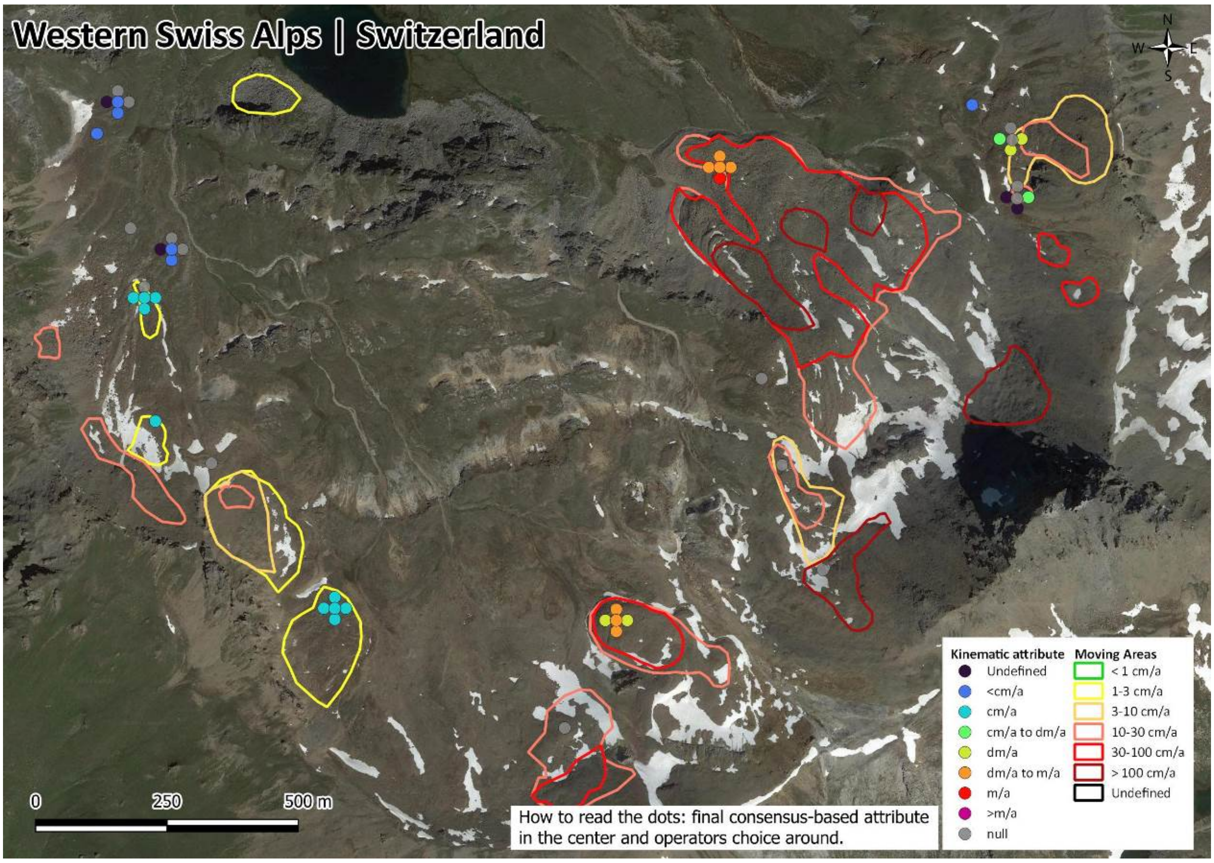
Carpathians | Romania
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0 250 500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.



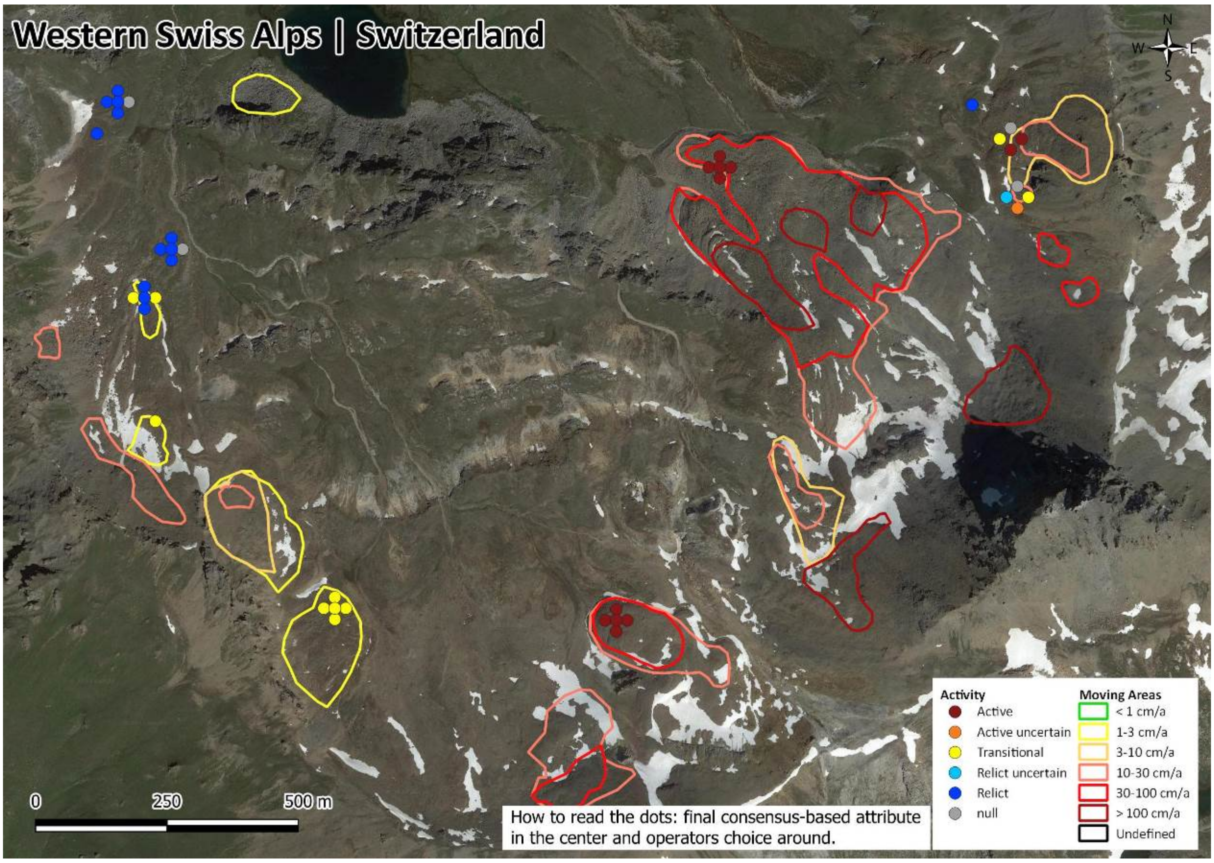
Carpathians | Romania
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0 250 500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.


Western Swiss Alps | Switzerland
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
0
250
500 m

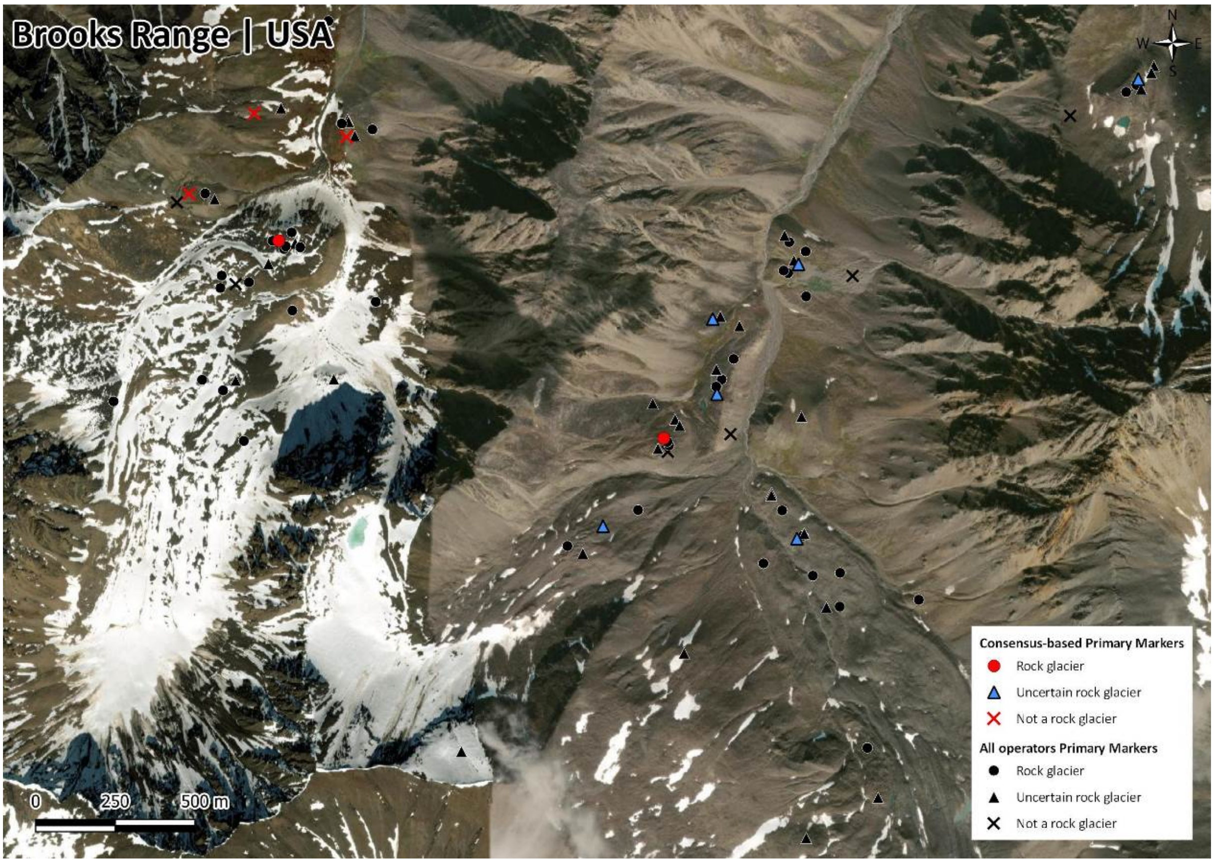

Western Swiss Alps | Switzerland
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators outlines
Extended
Restricted
Consensus-based outlines
Extended
Restricted
0
250
500 m



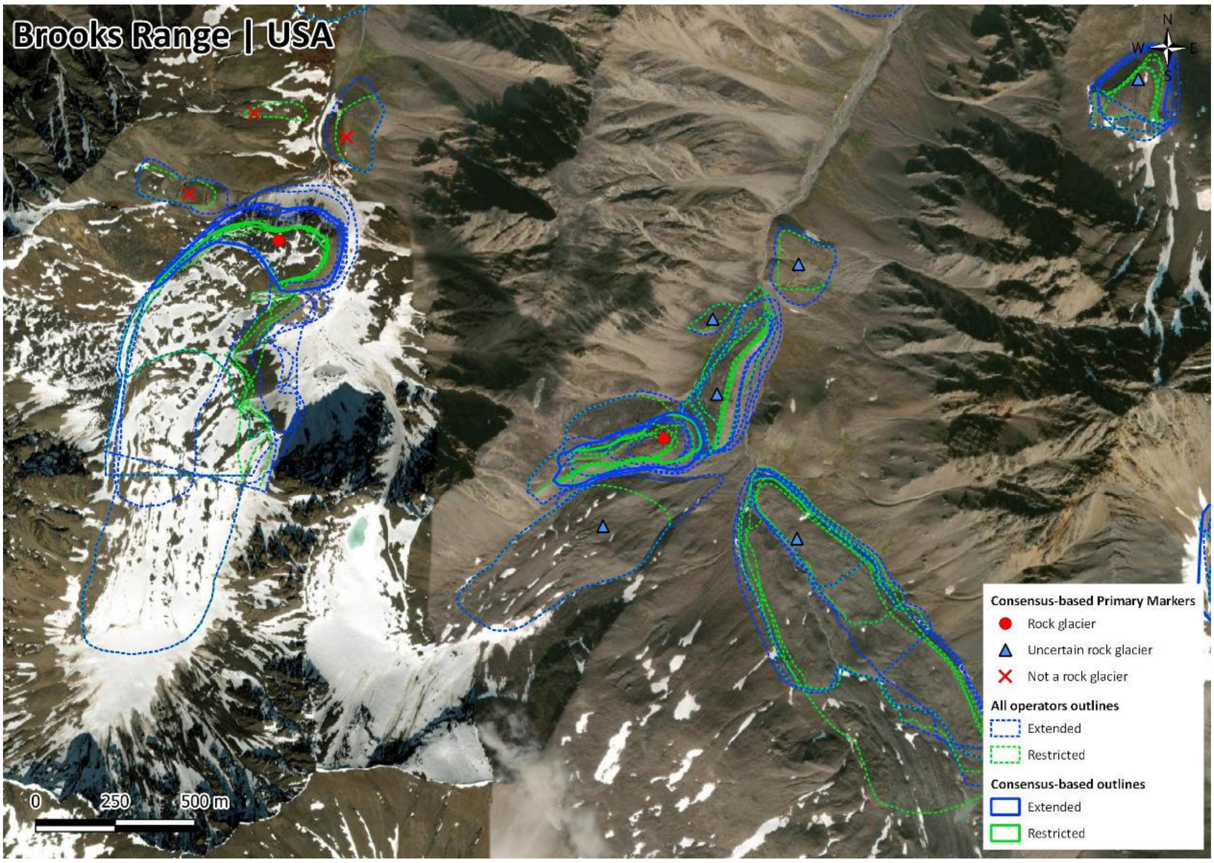
Western Swiss Alps | Switzerland
N
W
E
S
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.



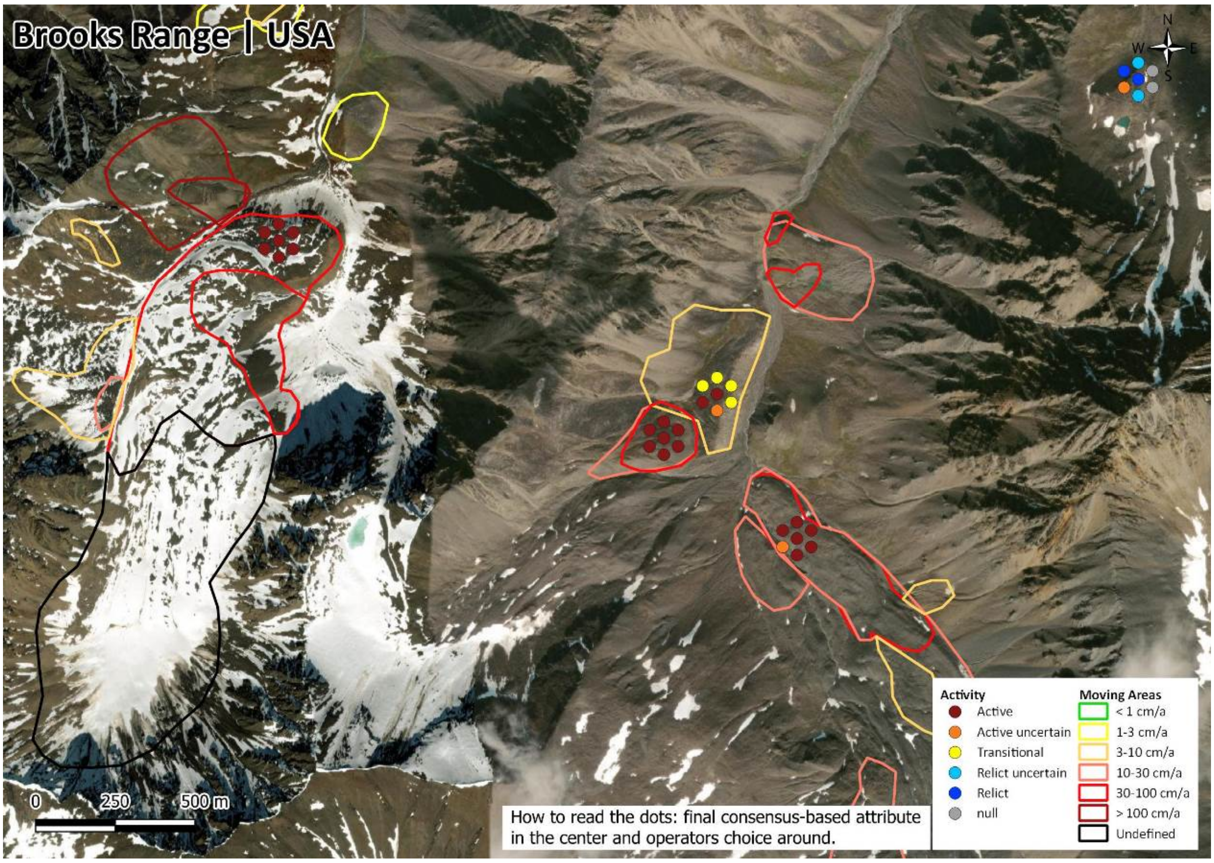
Western Swiss Alps | Switzerland
N
W
E
S
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.

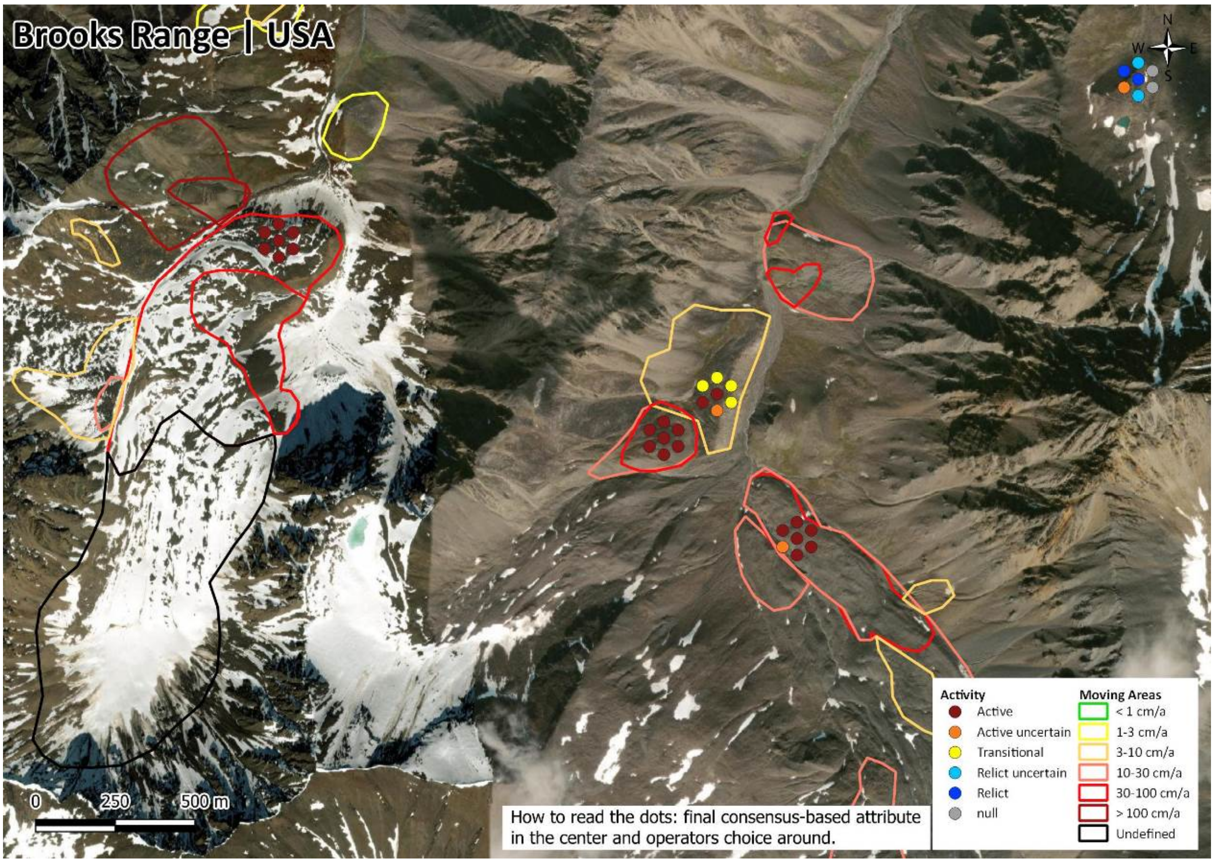


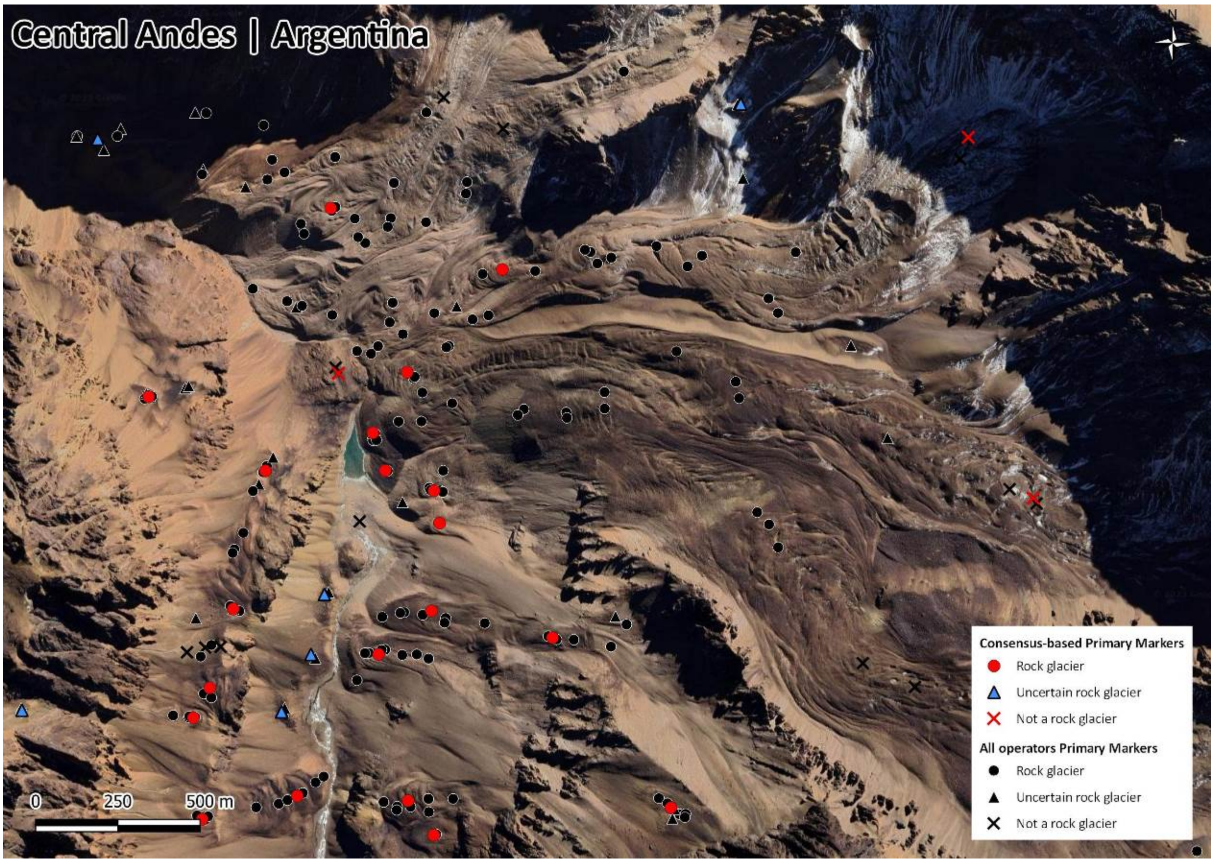
Brooks Range | USA
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
0
250
500 m



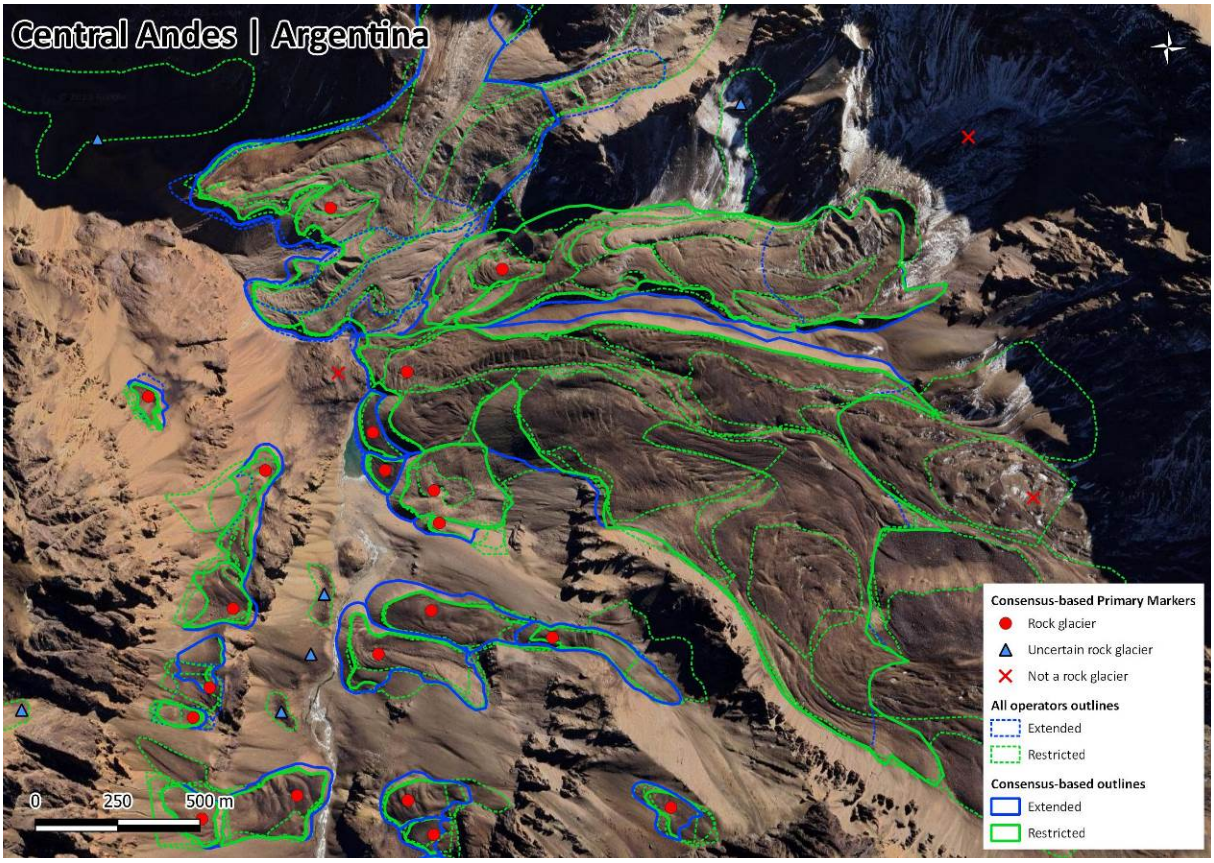
Brooks Range | USA
N
W
E
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators outlines
Extended
Restricted
Consensus-based outlines
Extended
Restricted
0
250
500 m


Brooks Range | USA
N
W
E
S
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined

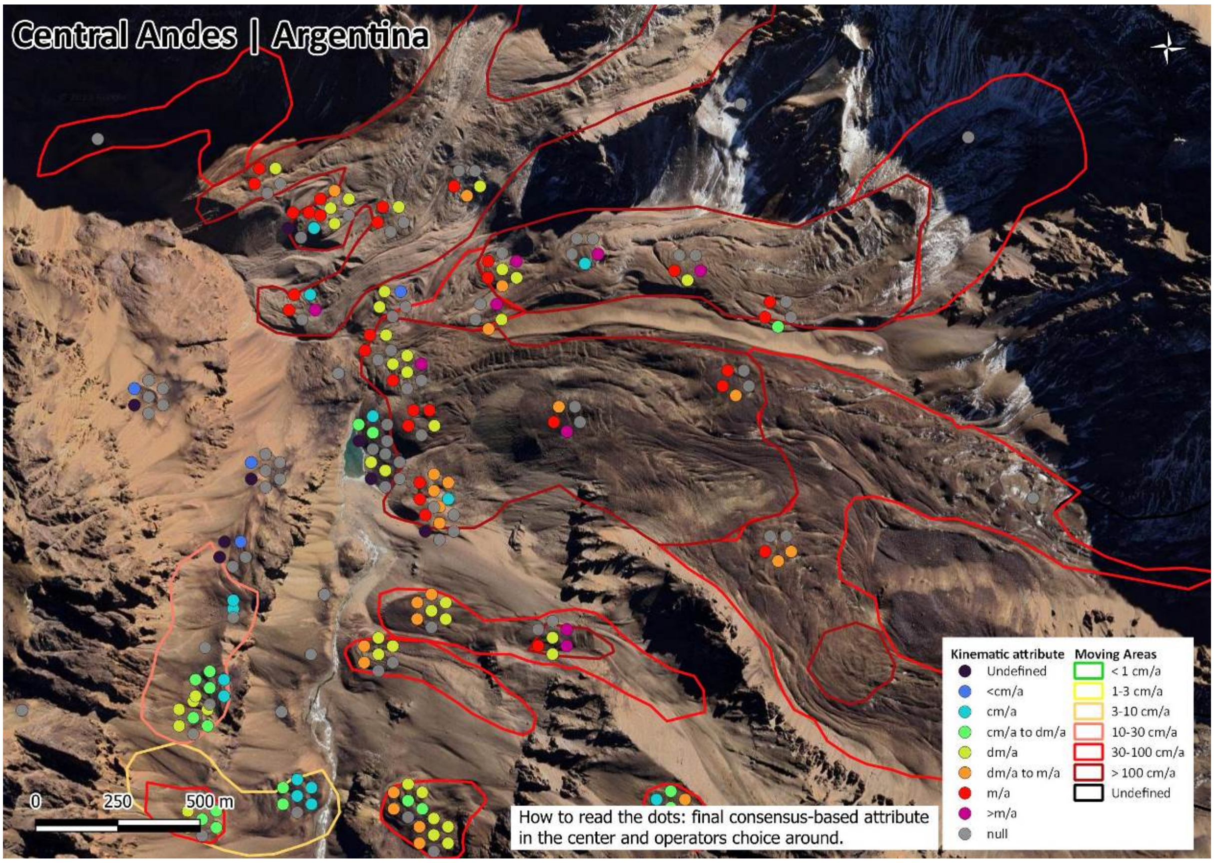

Brooks Range | USA
N
W
E
S
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined



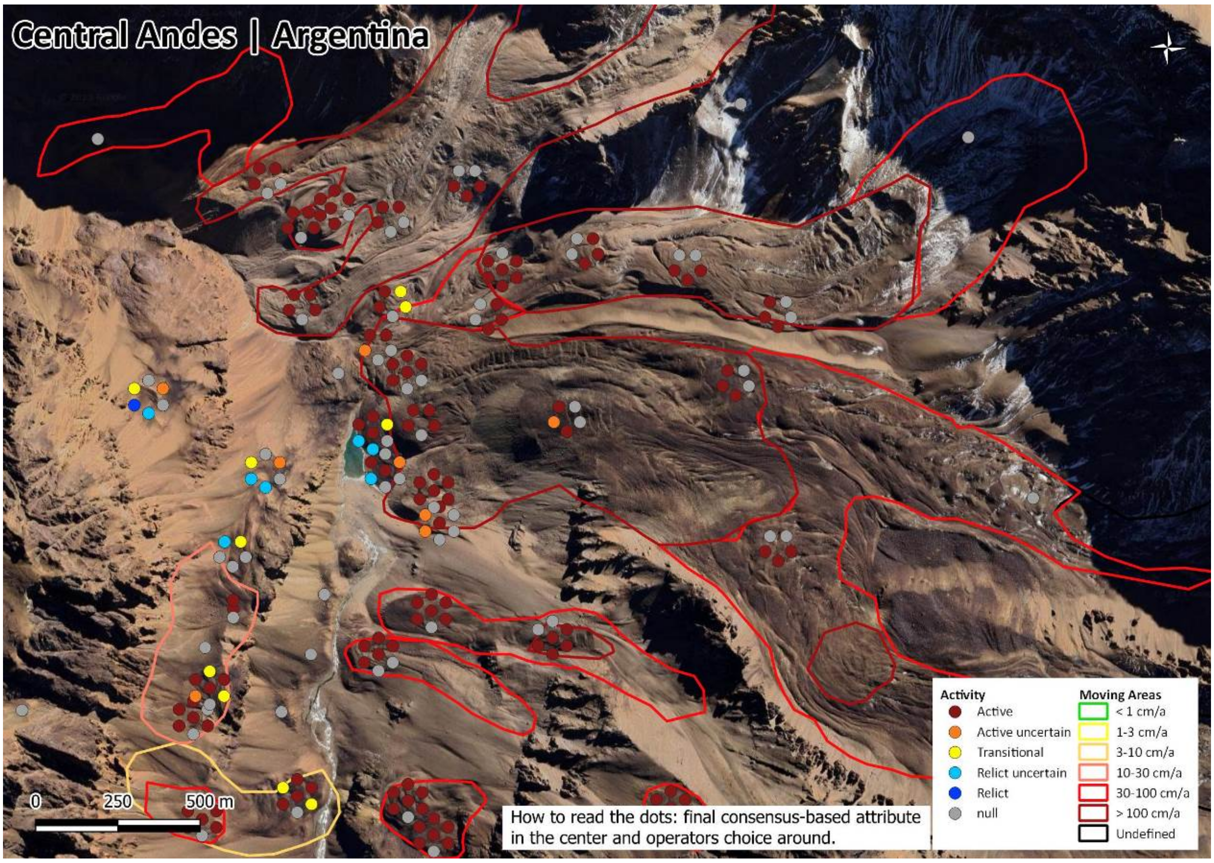
Central Andes | Argentina
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
0
250
500 m



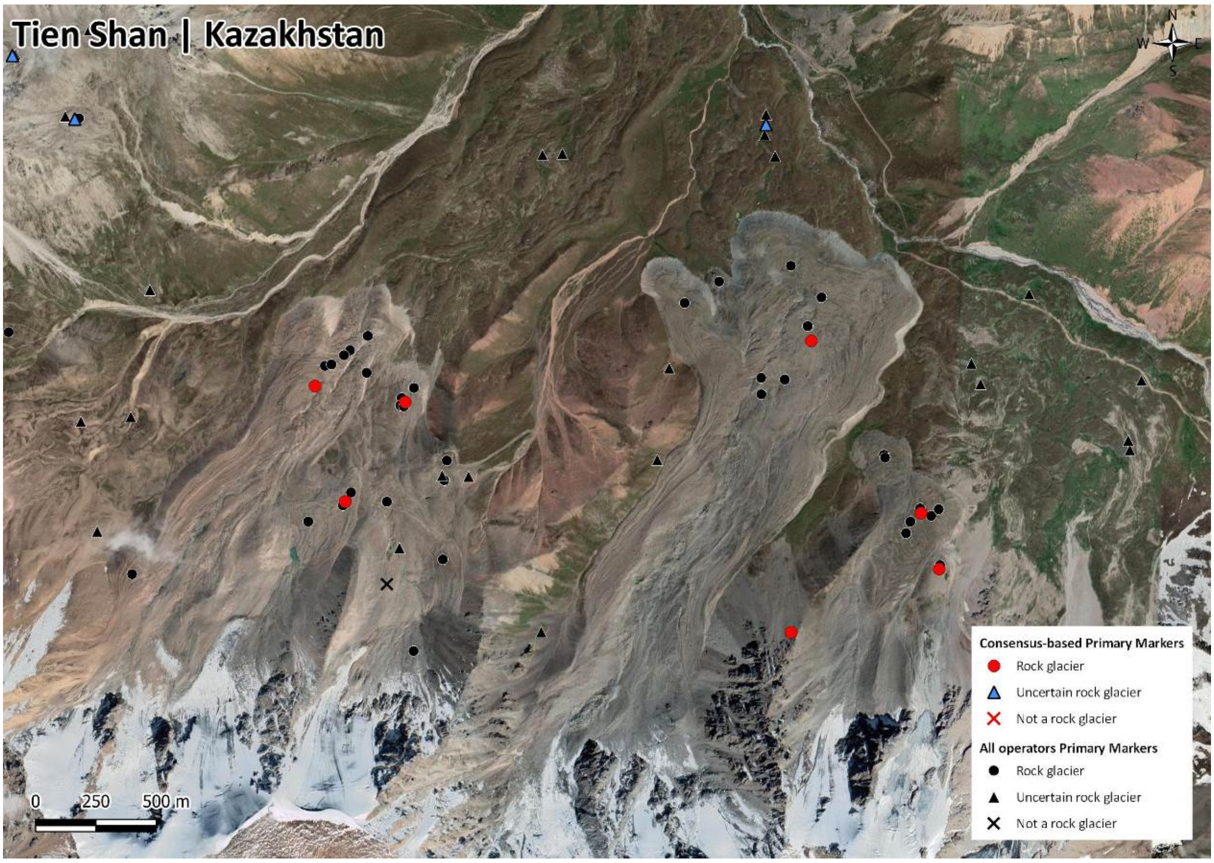
Central Andes | Argentina
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators outlines
Extended
Restricted
Consensus-based outlines
Extended
Restricted
0
250
500 m

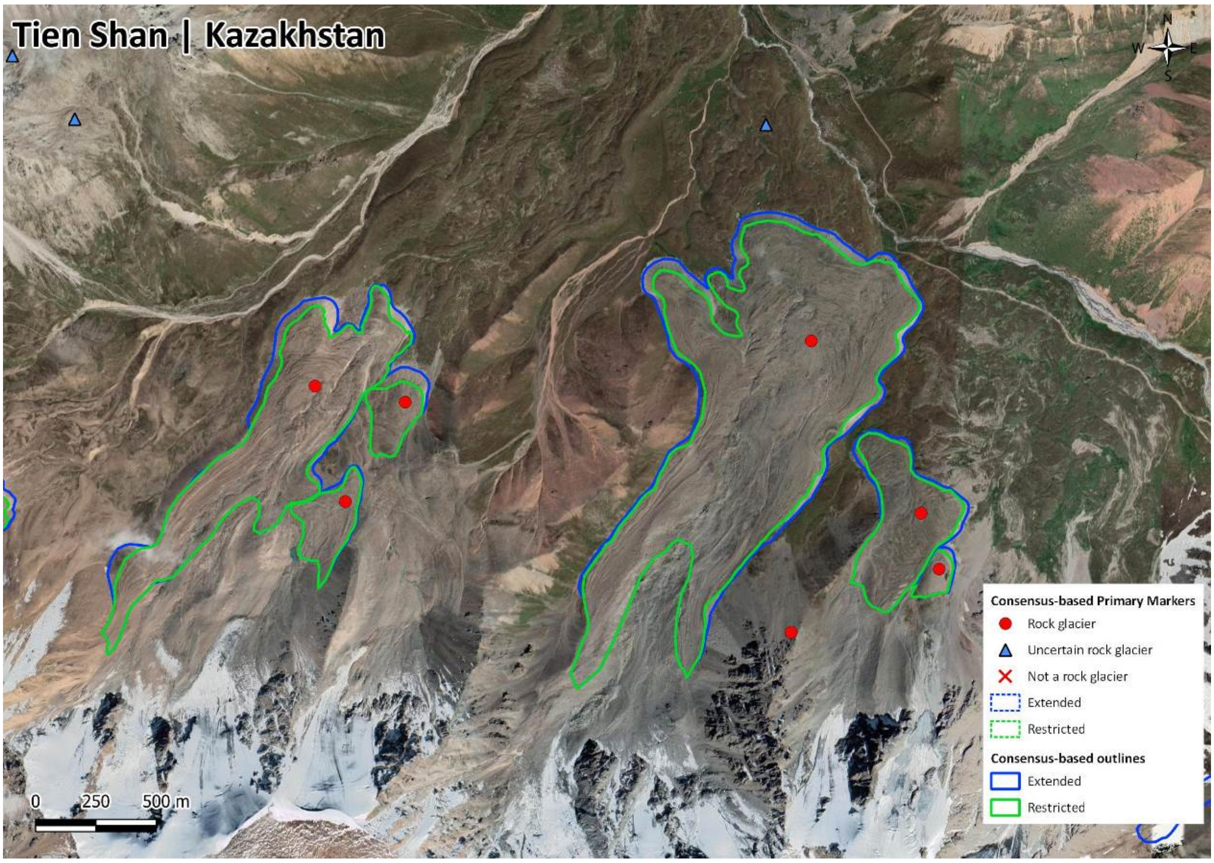


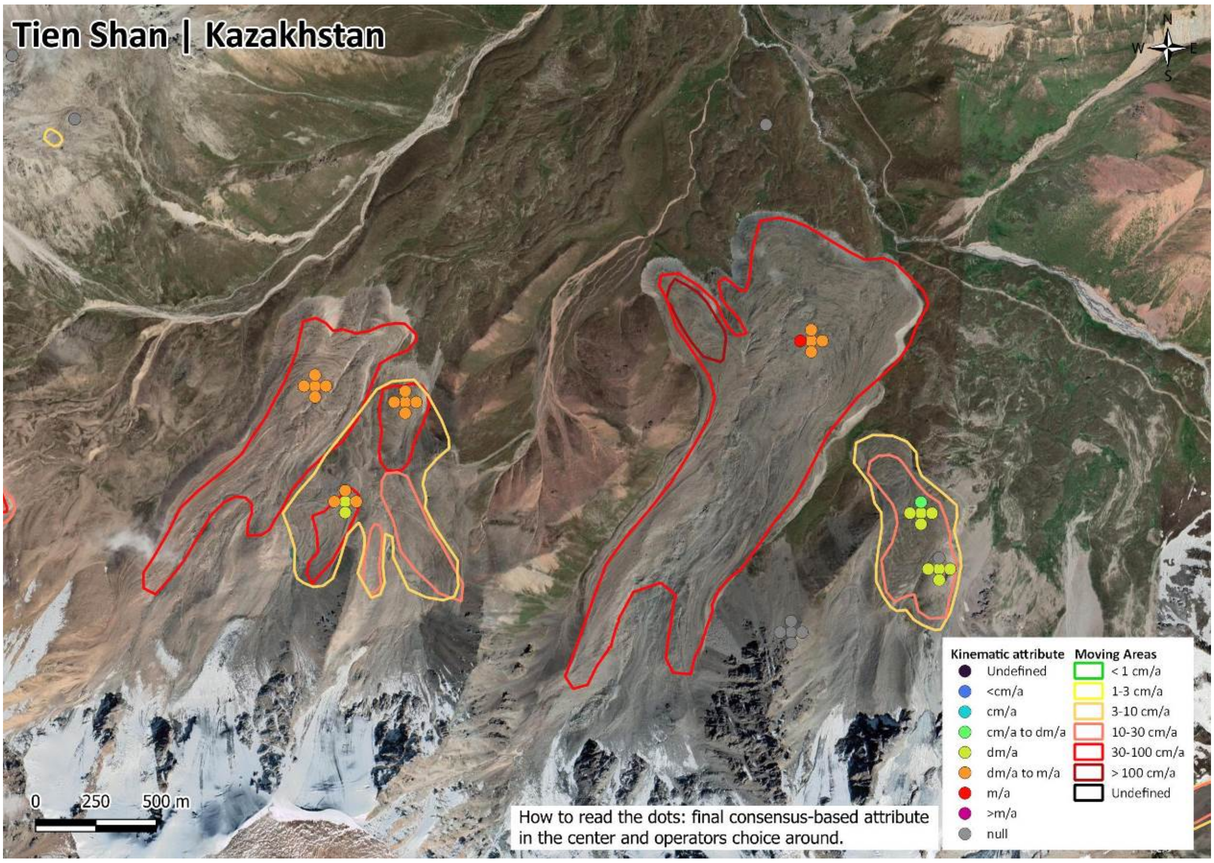
Central Andes | Argentina
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.

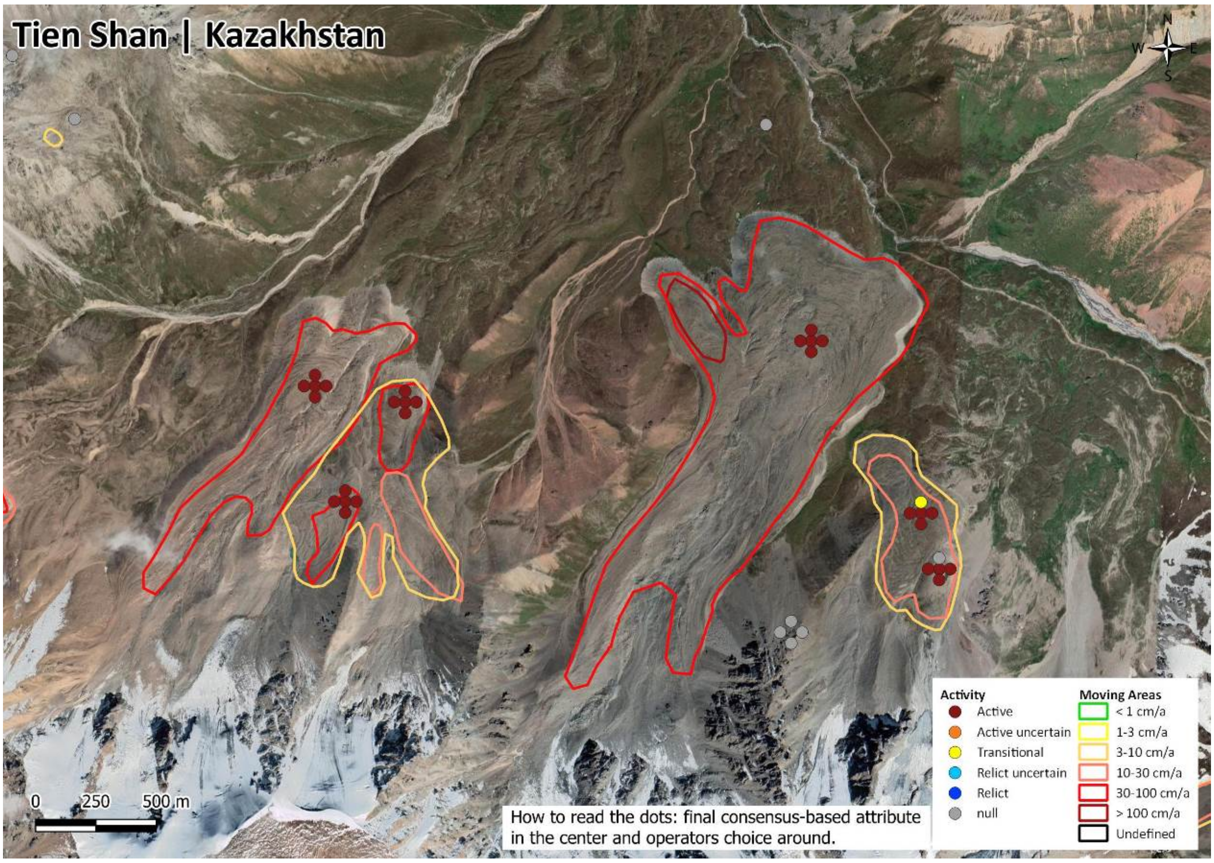


Central Andes | Argentina
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0
250
500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.

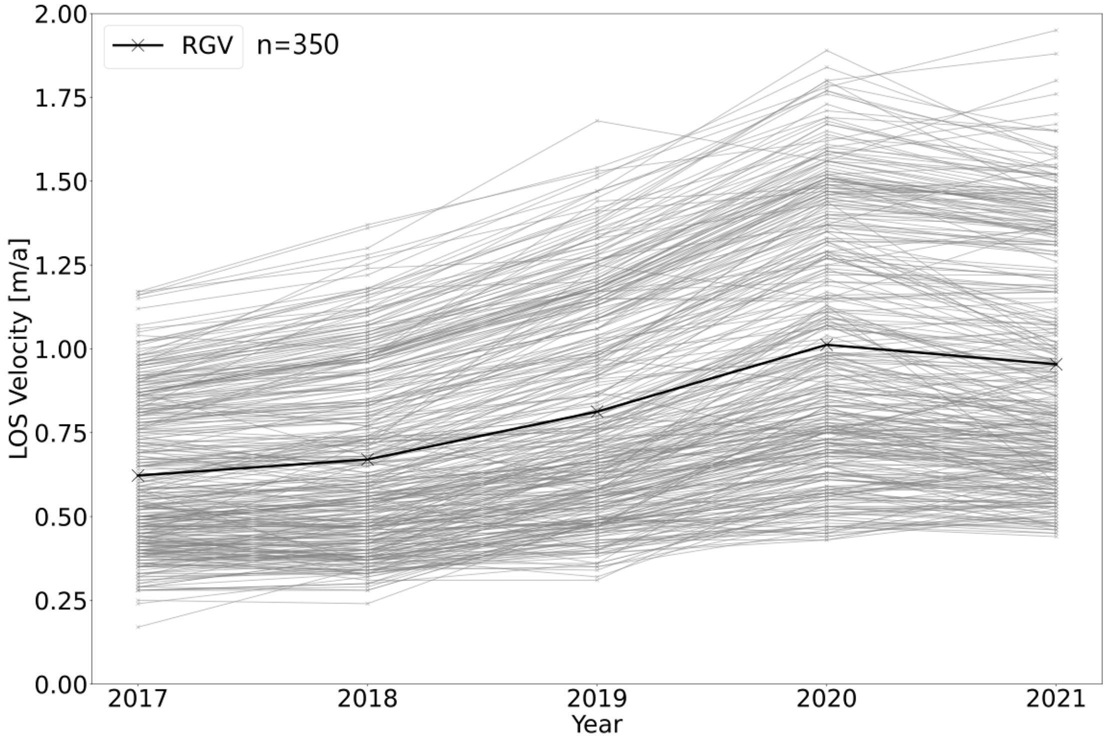

Tien Shan | Kazakhstan
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
All operators Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
0
250
500 m


Tien Shan | Kazakhstan
N
W
E
S
Consensus-based Primary Markers
Rock glacier
Uncertain rock glacier
Not a rock glacier
Extended
Restricted
Consensus-based outlines
Extended
Restricted
0
250
500 m

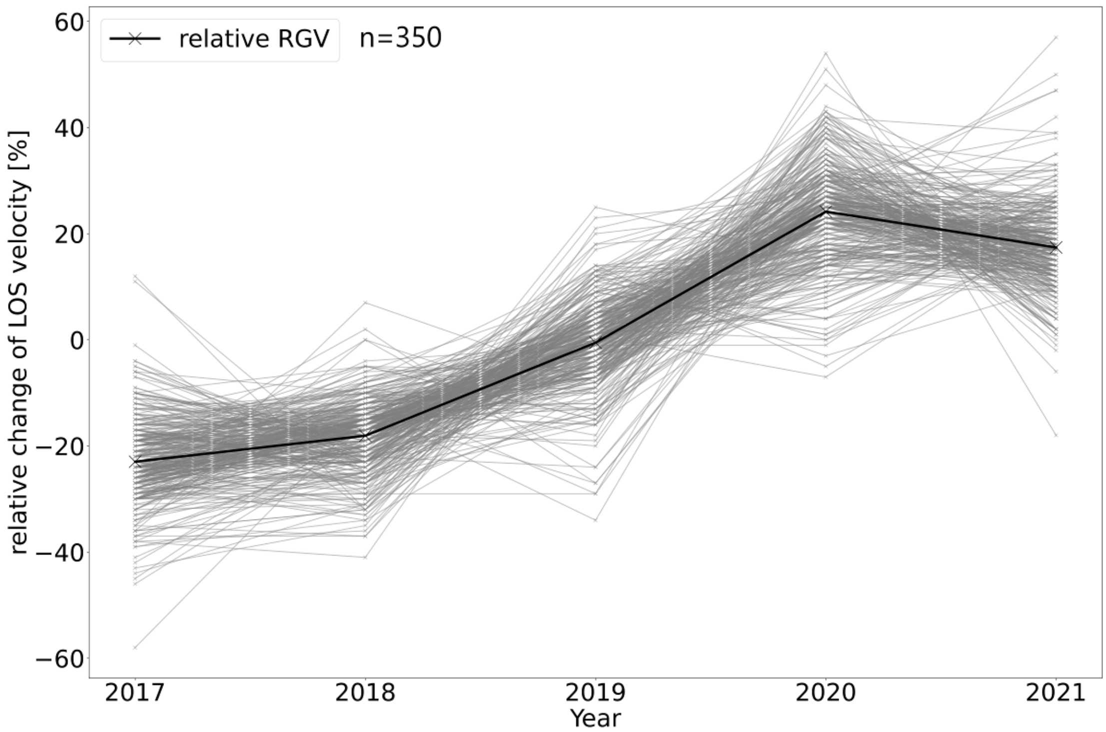

Tien Shan | Kazakhstan
Kinematic attribute
Undefined
<cm/a
cm/a
cm/a to dm/a
dm/a
dm/a to m/a
m/a
>m/a
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0 250 500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.


Tien Shan | Kazakhstan
Activity
Active
Active uncertain
Transitional
Relict uncertain
Relict
null
Moving Areas
< 1 cm/a
1-3 cm/a
3-10 cm/a
10-30 cm/a
30-100 cm/a
> 100 cm/a
Undefined
0 250 500 m
How to read the dots: final consensus-based attribute in the center and operators choice around.

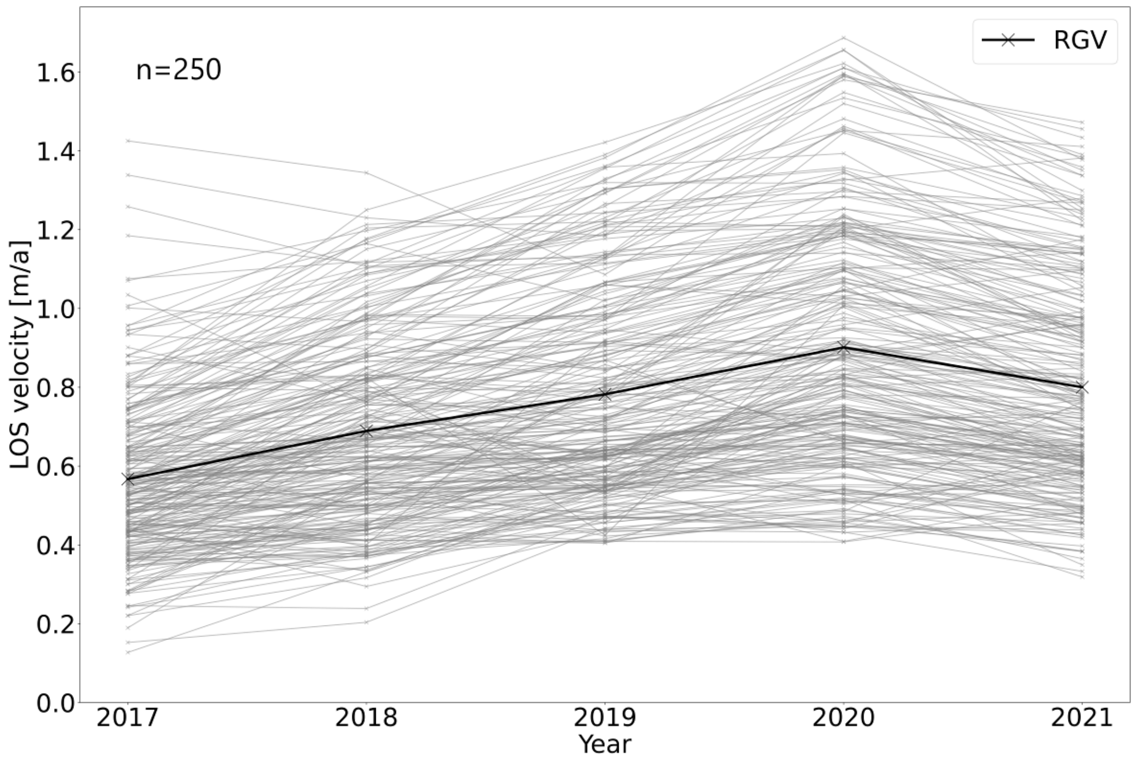
Annex 2: Examples of InSAR-derived RGV results in Switzerland



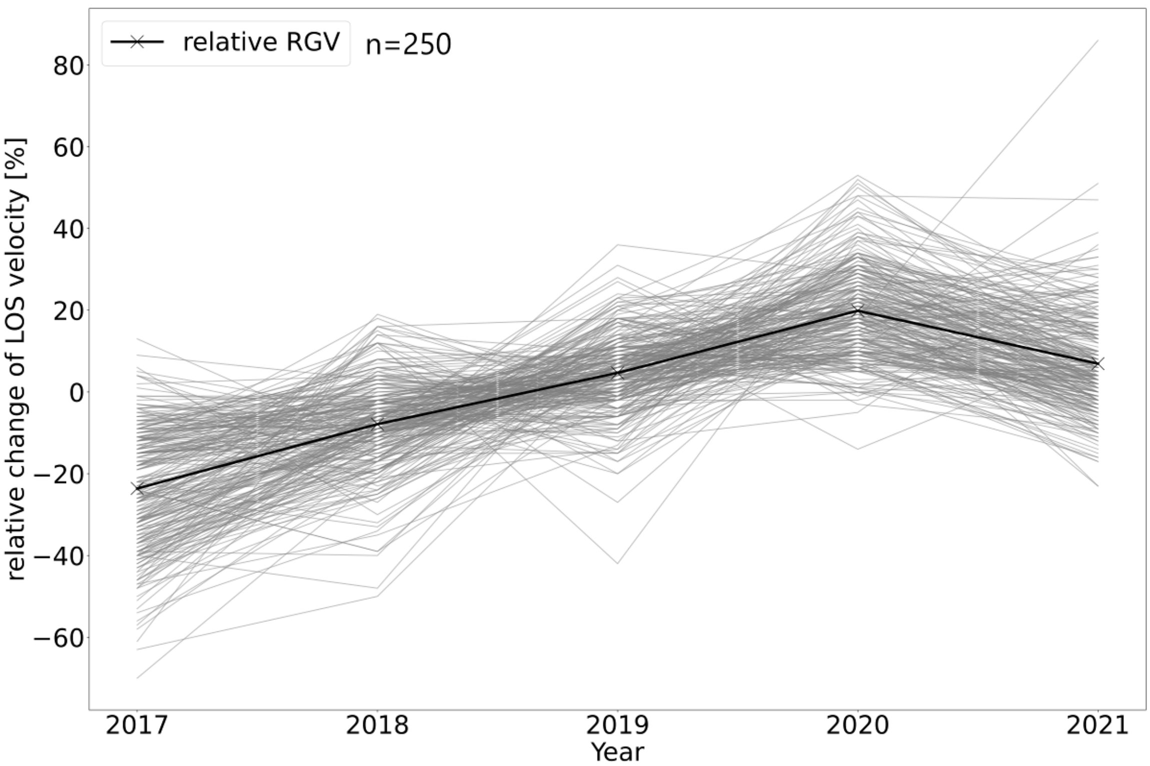
Distelhorn rock glacier: Annual LOS velocity in m/a between 2017 and 2021. The InSAR-derived RGV product is represented by the black line (average of selected time series after filtering and clustering). From Schmid (in prep).



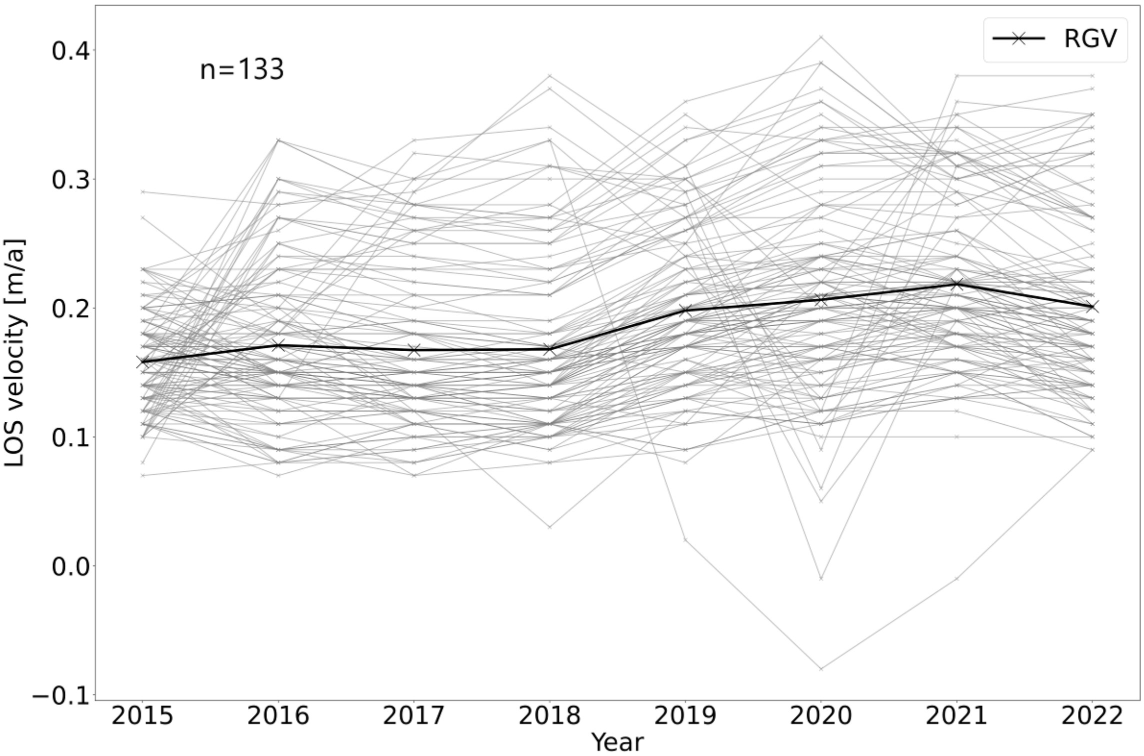
Distelhorn rock glacier: Annual relative change of LOS velocity in % between 2017 and 2021, relative to the mean of each time series. The relative InSAR-derived RGV product is represented by the black line. From Schmid (in prep).



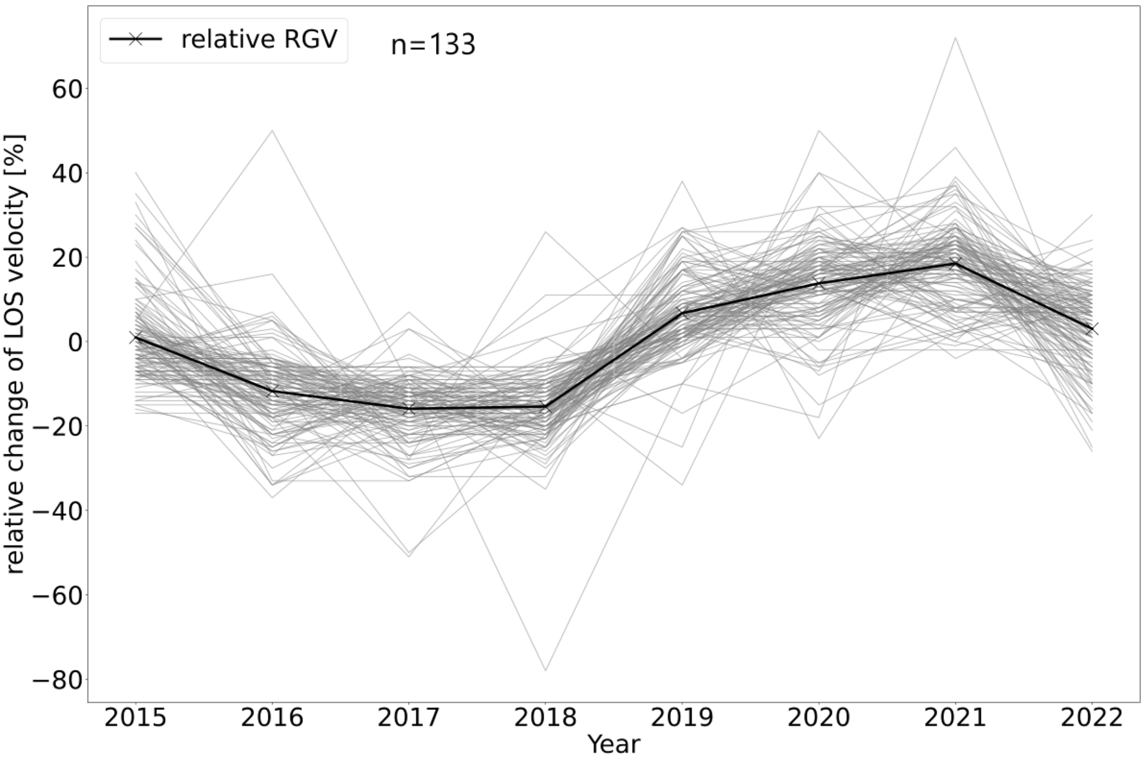
Becs-de-Bosson rock glacier: Annual LOS velocity in m/a between 2017 and 2021. The InSAR-derived RGV product is represented by the black line (average of selected time series after filtering and clustering). From Schmid (in prep).



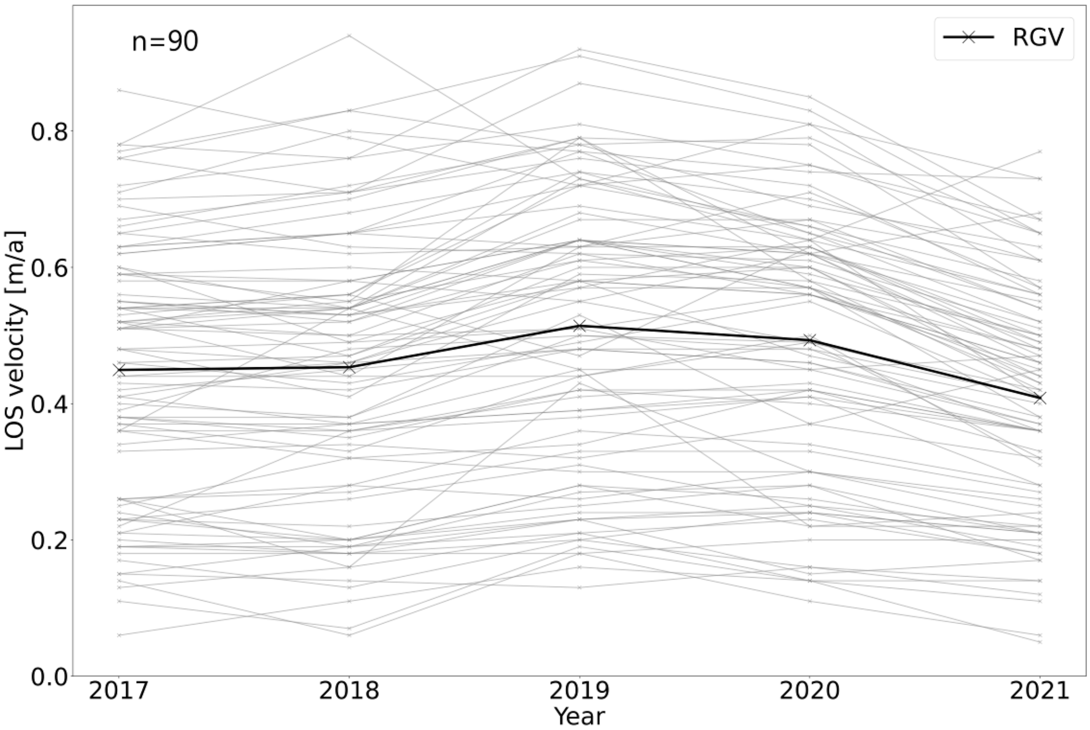
Becs-de-Bosson rock glacier: Annual relative change of LOS velocity in % between 2017 and 2021, relative to the mean of each time series. The relative InSAR-derived RGV product is represented by the black line. From Schmid (in prep).



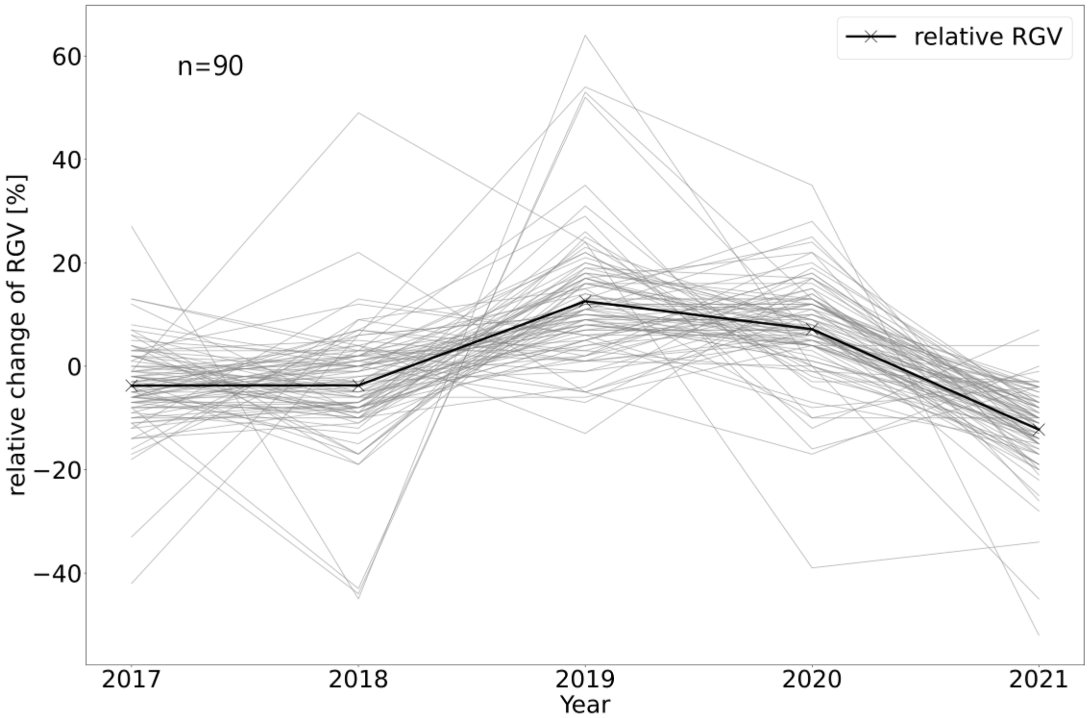
Bru rock glacier: Annual LOS velocity in m/a between 2015 and 2022. The InSAR-derived RGV product is represented by the black line (average of selected time series after filtering and clustering). From Schmid (in prep).



Bru Rock glacier: Annual relative change of LOS velocity in % between 2015 and 2022, relative to the mean of each time series. The relative InSAR-derived RGV product is represented by the black line. From Schmid (in prep).



Steintälli rock glacier: Annual LOS velocity in m/a between 2017 and 2021. The InSAR-derived RGV product is represented by the black line (average of selected time series after filtering and clustering). From Schmid (in prep).



Steintälli rock glacier: Annual relative change of LOS velocity in % between 2017 and 2021, relative to the mean of each time series. The relative InSAR-derived RGV product is represented by the black line. From Schmid (in prep).