esa climate change initiative
European Space Agency

Project Scientific Highlights (PSH)
Years 1, 2 and 3

Prepared by: Glaciers_cci consortium
Contract: 4000127593/19/I-NB
Name: Glaciers_cci+D6.4-3_PSH
Version: 3.0
Date: 15.07. 2022

Contact:
Frank Paul
Department of Geography
University of Zurich
frank.paul@geo.uzh.ch

Technical Officer:
Anna Maria Trofaier
ESA Climate Office

UNIVERSITY OF OSLO
University of Zurich UZH
UNIVERSITY OF LEEDS
GAMMA REMOTE SENSING
enveo

Document status sheet

Version	Date	Changes	Approval
0.1	15.10. 2020	Initial draft	
2.0	15.09. 2021	Update Year 2	
0.1	15.07. 2022	Update Year 3	

The work described in this report was done under ESA contract 4000127593/19/I-NB. Responsibility for the contents resides with the authors who prepared it.

Author team:
Frank Paul, Philipp Rastner (GIUZ); Thomas Nagler, Jan Wuite (ENVEO); Tazio Strozzi, Andreas Wiesmann (Gamma); Andreas Kääb, Livia Piermattei, Désirée Treichler (GUIO); Lin Gilbert, Andrew Shepherd (SEEL)

Glaciers_cci Technical Officer at ESA:
Anna Maria Trofaier

Table of Contents

1. Purpose

This document is providing an overview of the project scientific highlights of each year as documented in the Quarterly Progress Reports. It will be updated once per year.

2. Scientific highlights of Year 1

2.1 Glacier changes and lake development in High Mountain Asia

The recent publication by Treichler et al. (2019) demonstrates what can be achieved in regard to process understanding (water-cycle) by a PhD project, when combining information on glacier changes with lake level changes and climatic data about precipitation trends from re-analysis. The study also introduced new approaches when processing ICESat data in mountain regions and provided a new zonation of glacier regions for High Mountain Asia that will both form an important base for future studies in this region. In short, the study showed that the so-called Karakoram anomaly is rather centred further to the east over the West Kunlun Shan, and characterized by an almost stepwise increase in precipitation by the end of the 1990s (see Fig. 1).

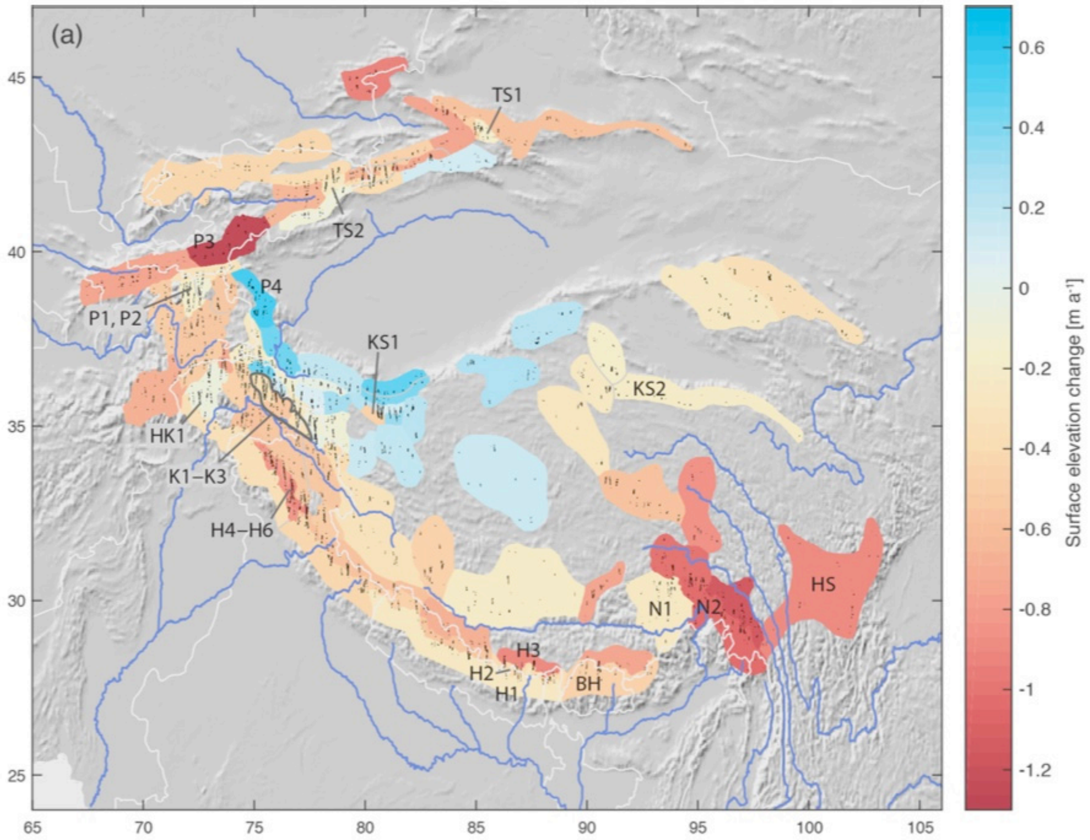


Fig. 1: ICESat-derived glacier elevation change rates from 2003 to 2008 for manually delineated zones.

2.2 Surge history of glaciers in the Karakoram

Satellite image time series (Corona, Hexagon, Landsat) were used to decipher the surge history of 27 glaciers in the central Karakoram back to the 1950s and beyond (considering a topographic map from 1937) in a new study by Paul (2020). The study interpreted the typical glacier surge and post-surge down-wasting patterns to determine the timing of surges beyond available imagery. The analysis revealed that most glaciers that have surged recently have also surged in the 1950s and 1960s (see Fig. 2), and very likely also before (back into the 19th century) at a roughly constant frequency. The so-called Karakoram Anomaly is thus seemingly a longer-term phenomenon.

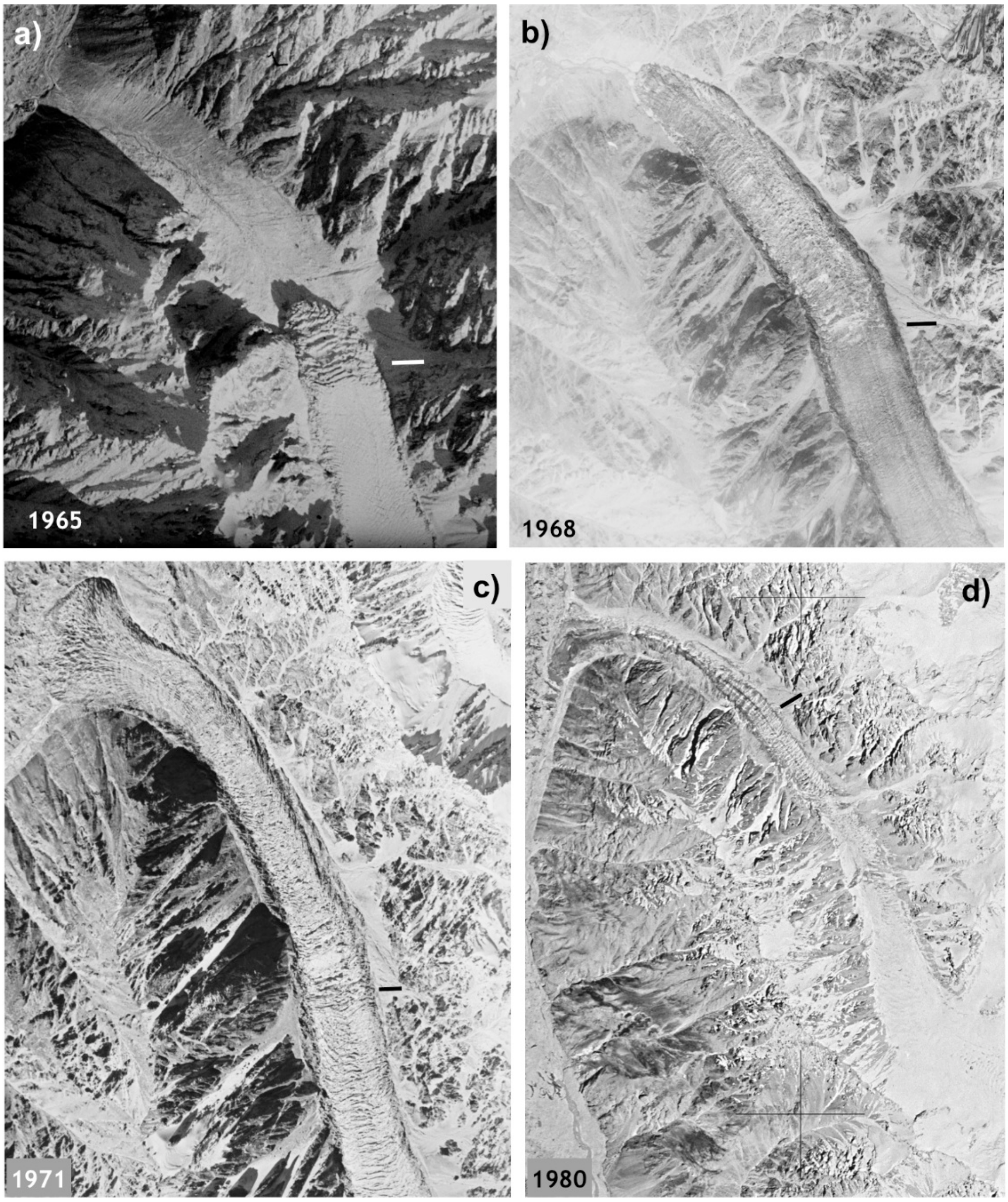


Fig. 2: The 1960s surge of First Feriole Glacier in: a) 1965, b) 1968, c) 1971 (all three from Corona), and d) 1980 (from Hexagon). The white and black bars mark the same position.

2.3 The recent surge of Negribreen in Svalbard

A new CCI+ study was published by Haga et al. (2020). They used a combination of many different datasets from ESA and others to decipher the massive recent surge of the tidewater glacier Negribreen, Svalbard. Negribreen, began actively surging after it experienced an initial collapse in summer 2016. The surge resulted in horizontal surface velocities of more than 25 m d^{-1}, making it one of the fastest-flowing glaciers in the archipelago (Fig. 3). As Negribreen is part of the Negribreen Glacier System, one of the largest glacier systems in Svalbard, investigating its current surge event provided important information on surge behaviour among tidewater glaciers within the region.

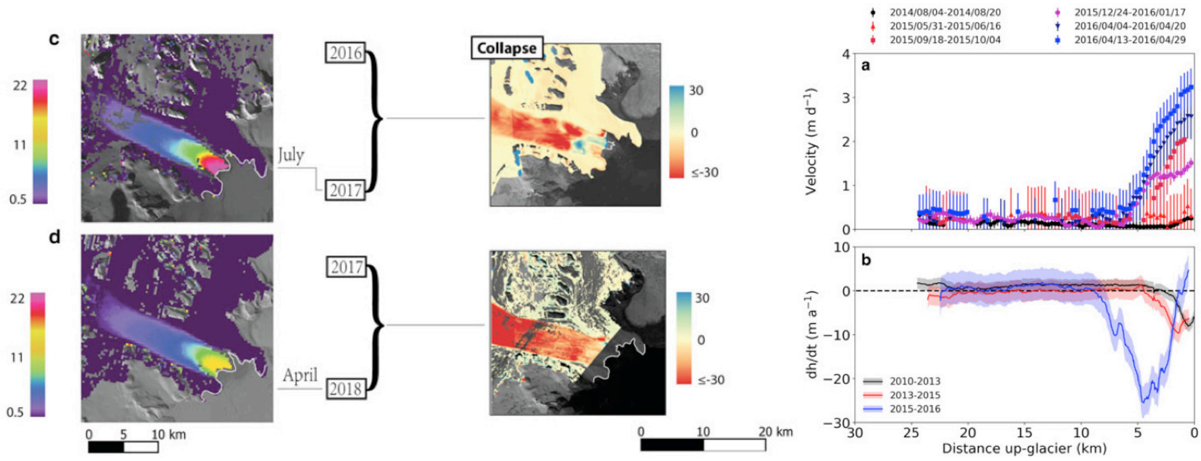
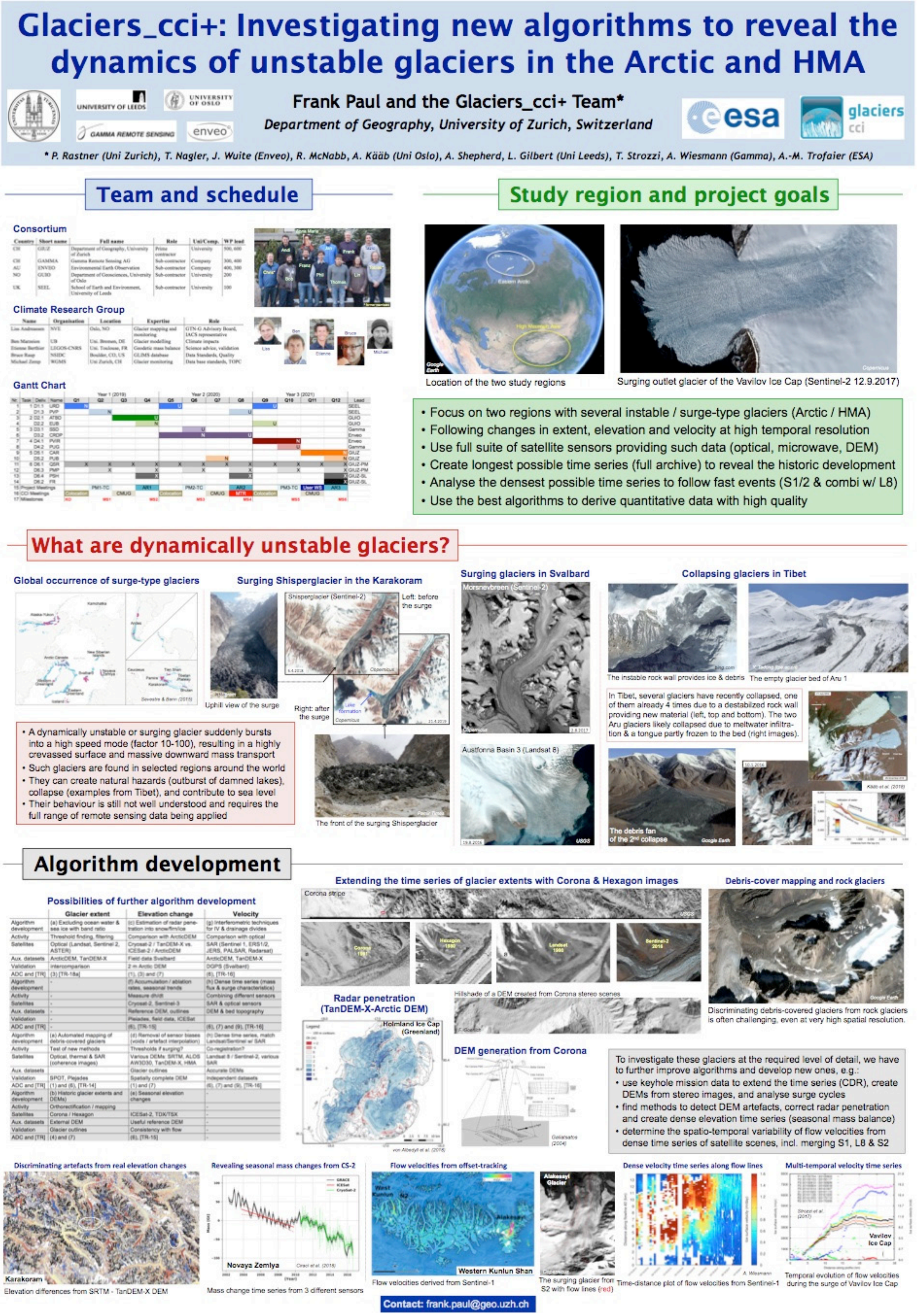


Fig. 3: Left: surface velocities in metres per for Negribreen in stages 3 (surge onset, marked c) and 4 (deceleration, marked d) of its surge. Middle: elevation differences given in metres per year. Right: Evolution of glacier dynamics along centre line during Stage 2. Panel a: Surface velocities (m d^{-1}) calculated every 300 m (points), the error bars are stable ground velocities. Panel b: Change in surface elevation between elevation products for all pixels between 3 and 5 km (from the coast).

2.4 Online Co-location Meeting

Due to the on-going COVID19 Pandemic, the co-location meeting had to be held online. This worked out very well and was clearly the highlight of Quarter 3 in 2020. The meeting provided a comprehensive overview on latest overarching developments and helped to set the stage for Phase 2 of CCI+ (and beyond). The meeting was much appreciated by the consortium that was actively involved in several sessions. In Fig. 4 we present a screen-shot of the poster that was presented by the Glaciers_cci+ team at the meeting, summarizing the proposed work in a more graphical form.



Glaciers_cci+: Investigating new algorithms to reveal the dynamics of unstable glaciers in the Arctic and HMA

Frank Paul and the Glaciers_cci+ Team*
Department of Geography, University of Zurich, Switzerland

* *P. Rastner (Uni Zurich), T. Nagler, J. Wuite (Enveo), R. McNabb, A. Kääb (Uni Oslo), A. Shepherd, L. Gilbert (Uni Leeds), T. Strozzi, A. Wiesmann (Gamma), A.-M. Trofaier (ESA)*

Team and schedule

Consortium

Country	Short name	Full name	Role	Uni/Comp.	WP lead
CH	GIUZ	Department of Geography, University of Zurich	Prime contractor	University	500, 600
CH	GAMMA	Gamma Remote Sensing AG	Sub-contractor	Company	300, 400
AU	ENVEO	Environmental Earth Observation	Sub-contractor	Company	400, 300
NO	GUIO	Department of Geosciences, University of Oslo	Sub-contractor	University	200
UK	SEEL	School of Earth and Environment, University of Leeds	Sub-contractor	University	100

Climate Research Group

Name	Organisation	Location	Expertise	Role
Liss Andreassen	NVE	Oslo, NO	Glacier mapping and monitoring	GTN-G Advisory Board, IACS representative
Ben Marzeion	UB	Uni. Bremen, DE	Glacier modelling	Climate impacts
Etienne Berthier	LEGOS-CNRS	Uni. Toulouse, FR	Geodetic mass balance	Science advice, validation
Bruce Raup	NSIDC	Boulder, CO, US	GLIMS database	Data Standards, Quality
Michael Zemp	WGMS	Uni Zurich, CH	Glacier monitoring	Data base standards, TOPC

Liss Ben Etienne Bruce Michael

Gantt Chart

Study region and project goals

Location of the two study regions

Surging outlet glacier of the Vavilov Ice Cap (Sentinel-2 12.9.2017)

- Focus on two regions with several instable / surge-type glaciers (Arctic / HMA)
- Following changes in extent, elevation and velocity at high temporal resolution
- Use full suite of satellite sensors providing such data (optical, microwave, DEM)
- Create longest possible time series (full archive) to reveal the historic development
- Analyse the densest possible time series to follow fast events (S1/2 & combi w/ L8)
- Use the best algorithms to derive quantitative data with high quality

What are dynamically unstable glaciers?

Global occurrence of surge-type glaciers

Sevestre & Benn (2015)

Surging Shisperglacier in the Karakoram

Shisperglacier (Sentinel-2)

Left: before the surge

Right: after the surge

Uphill view of the surge

The front of the surging Shisperglacier

- A dynamically unstable or surging glacier suddenly bursts into a high speed mode (factor 10-100), resulting in a highly crevassed surface and massive downward mass transport
- Such glaciers are found in selected regions around the world
- They can create natural hazards (outburst of damned lakes), collapse (examples from Tibet), and contribute to sea level
- Their behaviour is still not well understood and requires the full range of remote sensing data being applied

Surging glaciers in Svalbard

Monacobreen (Sentinel-2)

Austfonna Basin 3 (Landsat 8)

Collapsing glaciers in Tibet

The instable rock wall provides ice & debris

The empty glacier bed of Aru 1

In Tibet, several glaciers have recently collapsed, one of them already 4 times due to a destabilized rock wall providing new material (left, top and bottom). The two Aru glaciers likely collapsed due to meltwater infiltration & a tongue partly frozen to the bed (right images).

The debris fan of the 2nd collapse

Kääb et al. (2018)

Algorithm development

Possibilities of further algorithm development

	Glacier extent	Elevation change	Velocity
Algorithm development	(a) Excluding ocean water & sea ice with band ratio	(c) Estimation of radar penetration into snow/firn/ice	(g) Interferometric techniques for IV & drainage divides
Activity	Threshold finding, filtering	Comparison with ArcticDEM	Comparison with optical
Satellites	Optical (Landsat, Sentinel 2, ASTER)	Cryosat-2 / TanDEM-X vs. ICESat-2 / ArcticDEM	SAR (Sentinel 1, ERS1/2, JERS, PALSAR, Radarsat)
Aux. datasets	ArcticDEM, TanDEM-X	Field data Svalbard	ArcticDEM, TanDEM-X
Validation	intercomparison	2 m Arctic DEM	DGPS (Svalbard)
ADC and [TR]	(3) [TR-18a]	(1), (3) and (7)	(6), [TR-16]
Algorithm development	-	(f) Accumulation / ablation rates, seasonal trends	(h) Dense time series (mass flux & surge characteristics)
Activity	-	Measure dh/dt	Combining different sensors
Satellites	-	Cryosat-2, Sentinel-3	SAR & optical sensors
Aux. datasets	-	Reference DEM, outlines	DEM & bed topography
Validation	-	Pleiades, field data, ICESat	
ADC and [TR]	-	(6), [TR-15]	(6), (7) and (9), [TR-16]
Algorithm development	(a) Automated mapping of debris-covered glaciers	(d) Removal of sensor biases (voids / artefact interpolation)	(h) Dense time series, match Landsat/Sentinel w/ SAR
Activity	Test of new methods	Thresholds if surging?	Co-registration?
Satellites	Optical, thermal & SAR (coherence images)	Various DEMs: SRTM, ALOS AW3D30, TanDEM-X, HMA	Landsat 8 / Sentinel-2, various SAR
Aux. datasets		Glacier outlines	Accurate DEMs
Validation	SPOT, Pleiades	Spatially complete DEM	Independent datasets
ADC and [TR]	(1) and (6), [TR-14]	(1) and (7)	(6), (7) and (9), [TR-16]
Algorithm development	(b) Historic glacier extents and DEMs)	(e) Seasonal elevation changes	-
Activity	Orthorectification / mapping		-
Satellites	Corona / Hexagon	ICESat-2, TDX/TSX	-
Aux. datasets	External DEM	Useful reference DEM	-
Validation	Glacier outlines	Consistency with flow	-
ADC and [TR]	(4) and (7)	(6), [TR-15]	-

Extending the time series of glacier extents with Corona & Hexagon images

Corona stripe

Corona 1967 / Hexagon 1980 / Landsat 1998 / Sentinel-2 2018

Hillshade of a DEM created from Corona stereo scenes

Radar penetration (TanDEM-X-Arctic DEM)

Holmland Ice Cap (Greenland)

von Albedyll et al. (2018)

DEM generation from Corona

Galiatsatos (2004)

Debris-cover mapping and rock glaciers

Discriminating debris-covered glaciers from rock glaciers is often challenging, even at very high spatial resolution.

To investigate these glaciers at the required level of detail, we have to further improve algorithms and develop new ones, e.g.:
- use keyhole mission data to extend the time series (CDR), create DEMs from stereo images, and analyse surge cycles
- find methods to detect DEM artefacts, correct radar penetration and create dense elevation time series (seasonal mass balance)
- determine the spatio-temporal variability of flow velocities from dense time series of satellite scenes, incl. merging S1, L8 & S2

Discriminating artefacts from real elevation changes

Karakoram

Elevation differences from SRTM - TanDEM-X DEM

Revealing seasonal mass changes from CS-2

Novaya Zemlya

Ciracì et al. (2018)

Mass change time series from 3 different sensors

Flow velocities from offset-tracking

West Kunlun

Western Kunlun Shan

Flow velocities derived from Sentinel-1

Aliakesayi Glacier

The surging glacier from S2 with flow lines (red)

Dense velocity time series along flow lines

A. Wiesmann

Time-distance plot of flow velocities from Sentinel-1

Multi-temporal velocity time series

Strozzi et al. (2017)

Vavilov Ice Cap

Temporal evolution of flow velocities during the surge of Vavilov Ice Cap

Contact: frank.paul@geo.uzh.ch

Fig. 4: The poster that was presented by the Glaciers_cci+ team at the co-location meeting.

3. Scientific highlights of Year 2

3.1 Q4-2020: Glacier collapses around the world

The highlight of this quarter was the compilation and submission of a joint paper from a large author group describing observed collapses or detachments of flat glaciers around the world (Kääb et al. 2021). Whereas such events have been reported before, they only received the required attention after Kolkaglacier in the eastern Caucasus left its bed in 2002, rushing down a valley with 250 km/h and killing more than 100 people (Haeberli et al. 2004). This was considered a rare event that occurred under very special circumstances until two further glaciers in the Aru mountain range of Tibet also left their beds within a period of 3 months in 2016 (Kääb et al. 2018). The subsequent analysis of satellite image time series revealed several further detachments, that have been collected and jointly analysed for the present study. In Fig. 5 we present a related analysis of a Sentinel-2 image for the Peter the Great mountain range in Tajikistan with major events indicated.

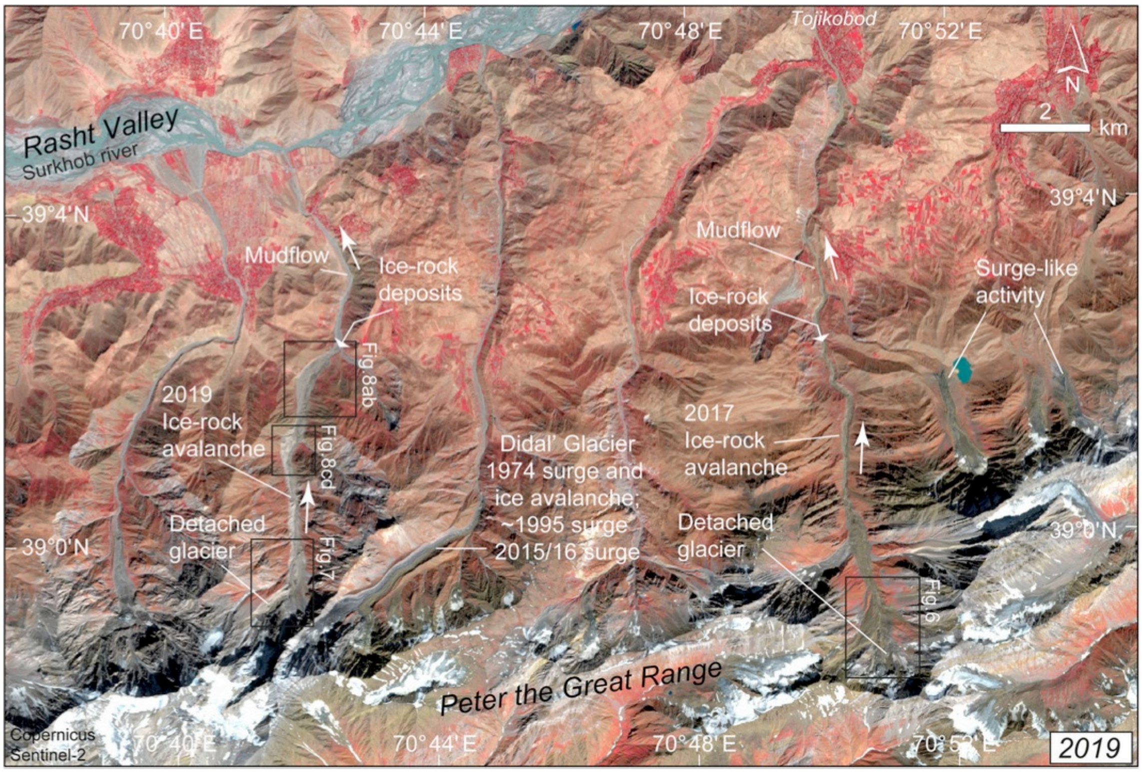
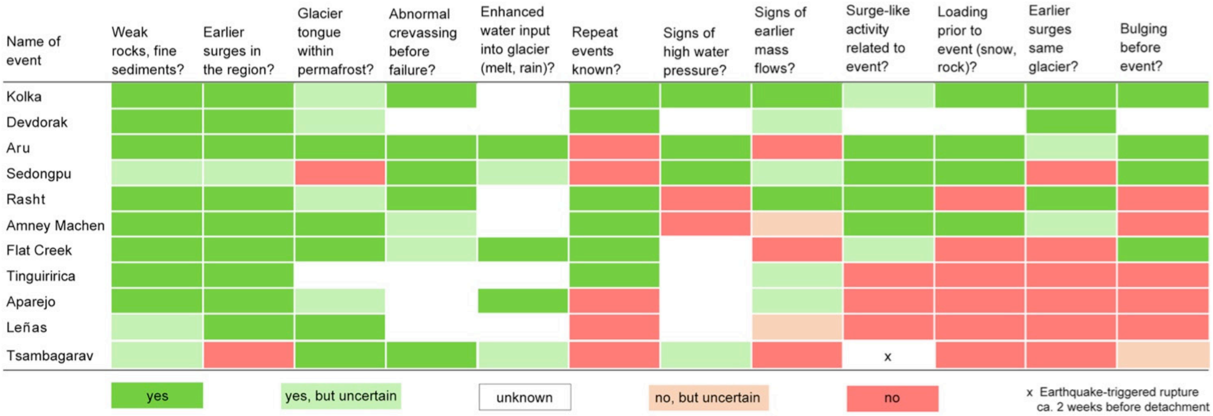


Fig. 5: Locations of the 2017 and 2019 ice–rock avalanches in the Peter the Great Range, Tajikistan. Satellite image: Sentinel-2, 19 September 2019 (credit: Copernicus Sentinel data).

A complete removal of a glacier from comparably flat bedrock is usually difficult to achieve and might be seen as an end-member of dynamic glacier behaviour. Such detachments might be triggered by impacts of climate change or special meteorological events (unusual rain). There is thus an urgent need to better understand the mechanisms behind these catastrophic but still comparably rare events. Figure 6 is presenting a related overview of the characteristics of these events revealing some commonalities but also differences. Further, more detailed investigations of individual events can be expected in the future.



Name of event	Weak rocks, fine sediments?	Earlier surges in the region?	Glacier tongue within permafrost?	Abnormal crevassing before failure?	Enhanced water input into glacier (melt, rain)?	Repeat events known?	Signs of high water pressure?	Signs of earlier mass flows?	Surge-like activity related to event?	Loading prior to event (snow, rock)?	Earlier surges same glacier?	Bulging before event?
Kolka	🟩	🟩	▨	🟩		🟩	🟩	🟩	▨	🟩	🟩	🟩
Devdorak	🟩	🟩	▨			🟩		▨			🟩	
Aru	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟩	▨	🟩
Sedongpu	▨	▨	🟥	🟩	▨	🟥	🟩	▨	🟩	🟩	🟥	🟩
Rasht	🟩	🟩	▨	🟩		🟩	🟥	🟩	🟩	🟥	🟩	🟥
Amney Machen	🟩	🟩	🟩	▨		🟩	🟥	🟧	🟩	🟩	▨	🟥
Flat Creek	🟩	🟩	🟩	▨	🟩	🟩		🟥	▨	🟥	🟥	🟩
Tinguiririca	🟩	🟩				🟩		▨	🟥	🟥	🟥	🟥
Aparejo	🟩	🟩	▨		🟩	🟥		▨	🟥	🟥	🟥	🟥
Leñas	▨	🟩	🟩			🟥		🟧	🟥	🟥	🟥	🟥
Tsambagarav	▨	🟥	🟩	🟩	▨	🟥	▨	🟥	x	🟥	🟥	🟧

🟩 yes
▨ yes, but uncertain
☐ unknown
🟧 no, but uncertain
🟥 no
x Earthquake-triggered rupture ca. 2 weeks before detachment

Fig. 6: Possible indicators for and factors involved in low-angle glacier detachments. The columns and rows are roughly sorted according to increasing number of "no" entries towards the lower right (taken from Kääb et al. 2021)

The study was also featured on the following ESA and CCI webpages:
climate.esa.int/en/news-events/low-angle-mountain-glacier-detachments-more-frequent-than-thought/
www.esa.int/Applications/Observing_the_Earth/Glacier_avalanches_more_common_than_thought

3.2 Q1-2021: An inventory of ice marginal lakes in Greenland

The publication of the study by How et al. (2021) in Scientific Reports is the main outcome of the work in Option 6 of Glaciers_cci and presenting the improved possibilities for glacier lake detection when several datasets (e.g. Sentinel-1/2, DEMs) and methods are combined. Figure 7 is presenting selected results of the analysis for a sub-region of Greenland.

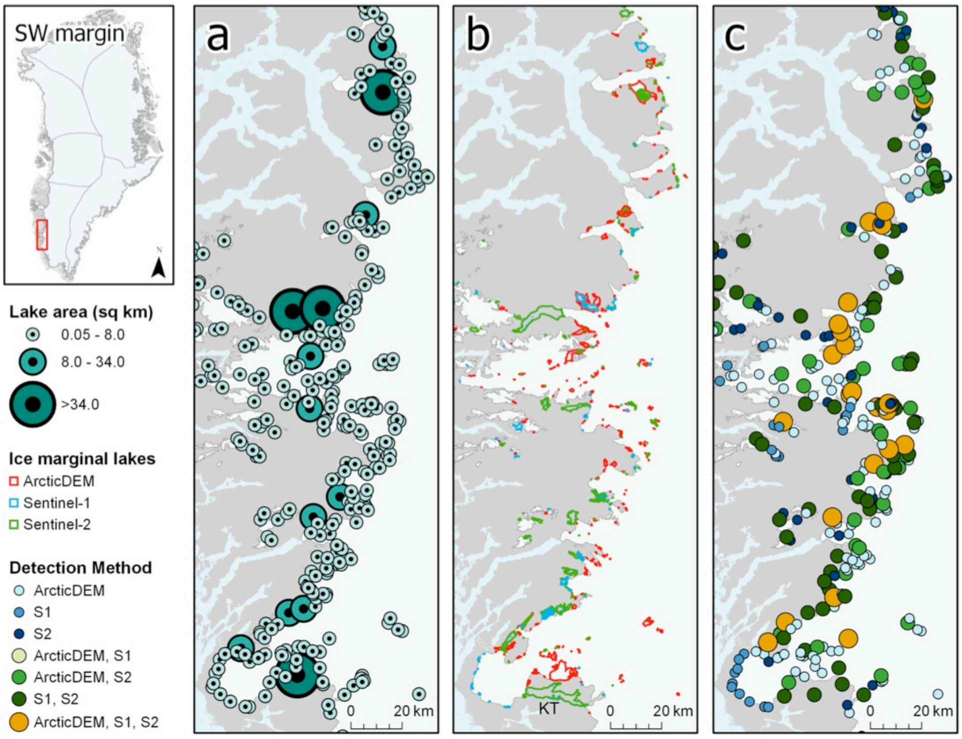


Fig. 7: Ice marginal lakes over a sub-section of the SW ice sheet margin, with (a) lake area, (b) lake shape determined by each method, and (c) detection method (from How et al. 2021).

The study identified 3347 ice marginal lakes >0.05 km^2 and revealed a clear upward trend in the number of lakes since 1985 with related consequences for flood hazards on a local scale to impacts on sea-level rise on the global scale. For the latter, the retention of melt water not contributing to sea level can now be better estimated. The dataset also served for validation of approaches that map lakes at a coarser spatial resolution in the Lakes_cci project.

3.3 Q2-2021: Global glacier mass loss

In this quarter the study by Hugonnet et al. (2021) was published. For the first time, an assessment of the geodetic mass balance of nearly all 215,000 glaciers in the world over the period 2000-2019 was performed using time series of ASTER stereo images and automated DEM processing. Members of the Glaciers_cci team have contributed to the methods applied in this study and are co-authors. Apart from the numerous applications of this new dataset in future studies (e.g. calibration of mass balance models), a main result of this global overview is that the mass loss of glaciers has further increased over the past 20 years and that mass loss is now everywhere the dominant feature. This trend despite strongly shrinking glacier areas implies that glacier extents are still out of balance with the current climate and will continue shrinking in the future, even if global temperatures would not increase further (see also: https://climate.esa.int/en/news-events/recent-acceleration-in-global-glacier-melt-study-warns).

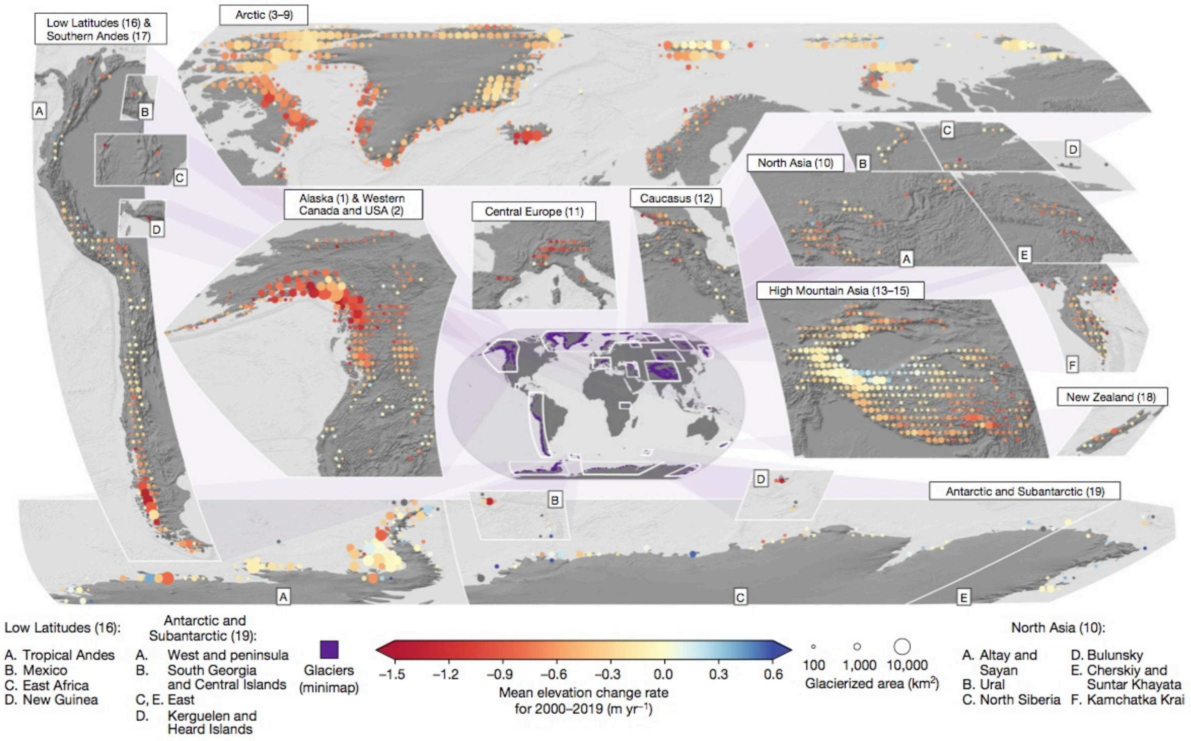


Fig. 8: Glacier elevation change between 2000 and 2019 for various subregions. The mean change rate is aggregated for tiles of 1° × 1° below 60° latitude, 2° × 1° (from 60° to 74°) and 2° × 2° above 74° latitude, thus representing similar surface areas of approximately 10,000 km^2. Disks scale with the glacierized area of each tile and are coloured according to the mean elevation change rate (coloured in grey if less than 50% of the surface is covered by observations or if the 95% confidence interval is larger than 1 m yr^{-1}; only applies to 0.4% of the glacierized area) shown on top of a world hillshade. Tiles with glacierized areas less than or equal to 10 km^2 are displayed at the same minimum size. (from Hugonnet et al. 2021).

3.4 Q3-2021: The Chamoli disaster

On 7 Feb 2021 a large mass of rock and ice detached at an elevation of 5500 m below the 6060 m high Ronti Peak in Uttarakhand, India, and formed a devastating debris flow that killed 200 people at the Tapovan hydropower construction site 25 km downstream (Fig. 9). Under the lead of Dan Shugar from the University of Calgary a team of experts from all over the world came together and analysed a wide range of before/after satellite images and DEMs to decipher the reasons and time line of the event. The result of the analysis was published a few months later in the journal Science (Shugar et al. 2021). It was revealed that a mixture of 80% rock with 20% ice was ideal to melt all ice and transform the crushed rock into a deadly and far reaching debris flow (Fig. 10), its levels being up to 220 m above the valley floor.

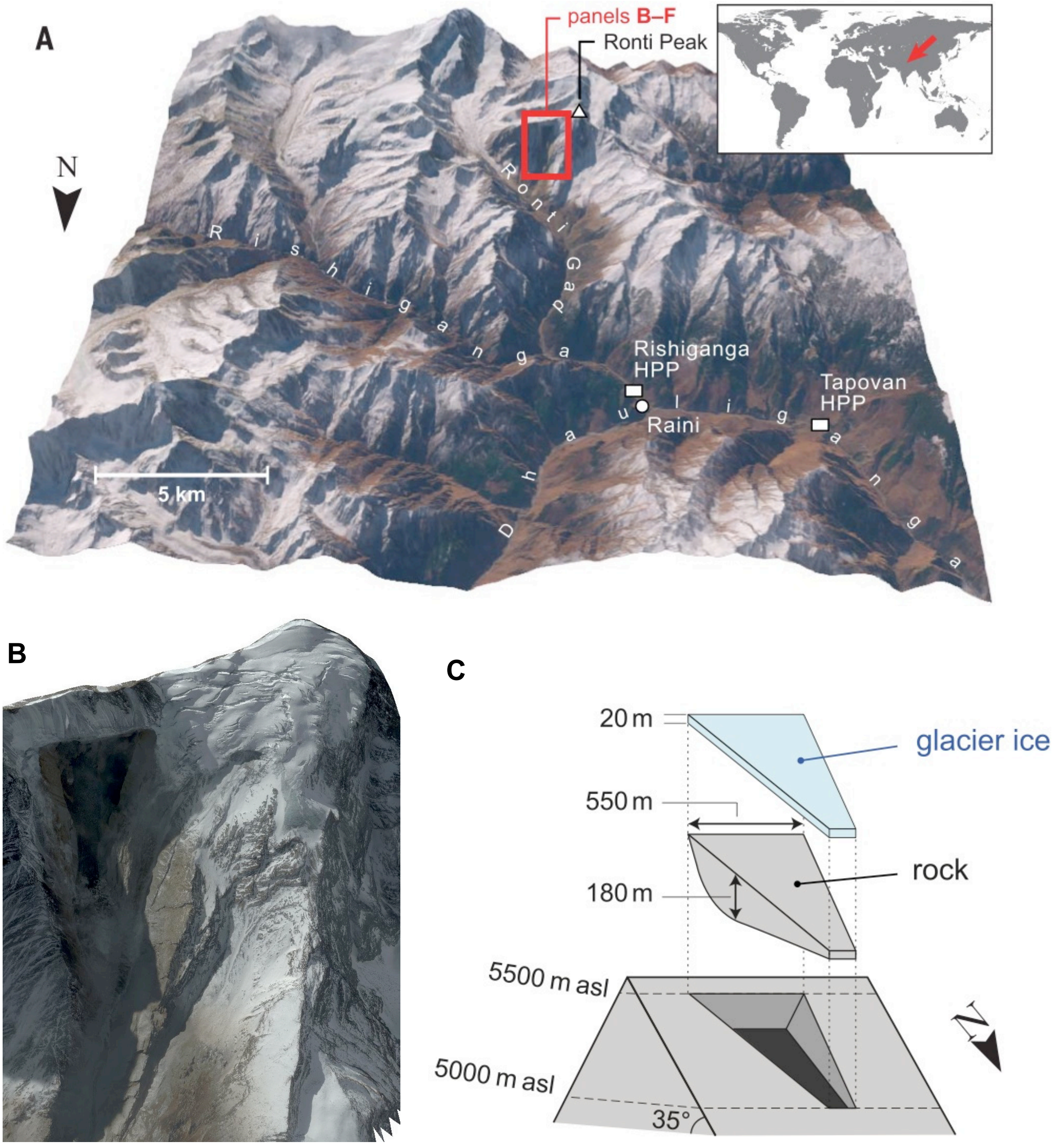


Fig. 9: (A) Region overview, (B) the scar in the mountain flank as seen by Pleiades on 9.2. 2021, (C) conceptual model of the rock/ice slab and scar (from Shugar et al. 2021).

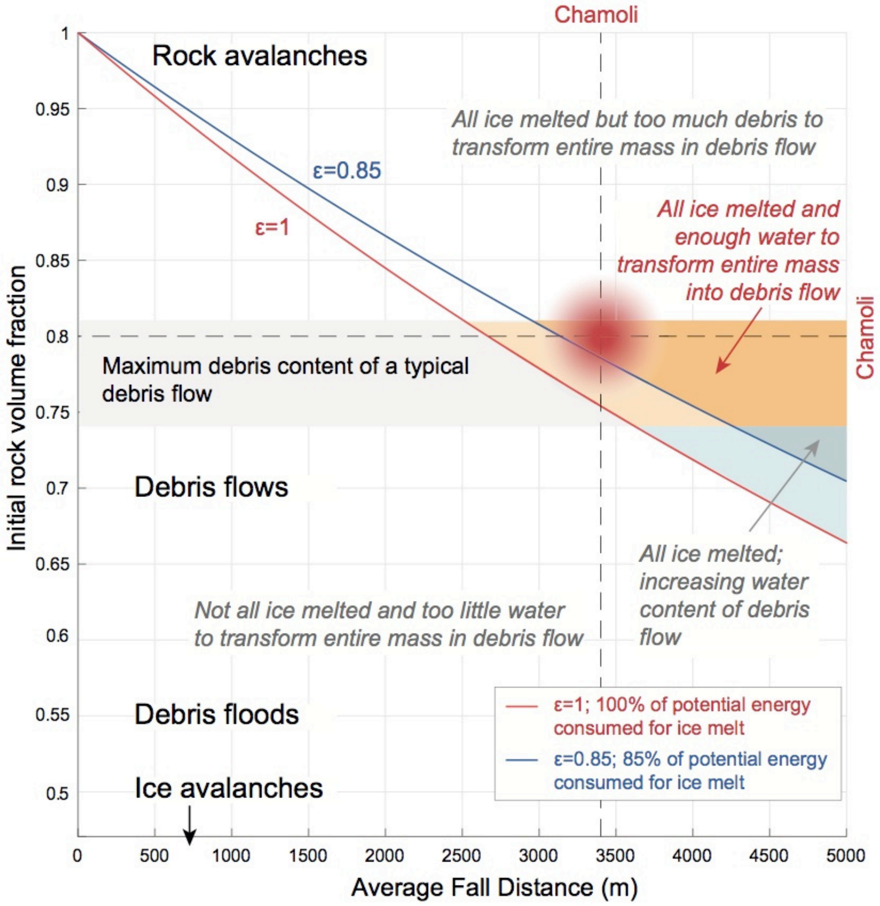


Fig. 10: Rock volume fraction that would be able to melt all ice during fall as a function of average fall distance. The vertical dashed line at 3400 m represents the mean fall distance between the site of the initial detachment and the Rishiganga hydropower project. The vertical dashed line indicates the initial rock volume fraction of the detachment of about 0.8. The Chamoli rock and ice avalanche had a combination of rock-ice fraction and fall distance that enabled most ice to be melted and to transform into a debris flow (orange area, taken from Shugar et al. 2021).

The study was also featured on an ESA webpage:
www.esa.int/Applications/Observing_the_Earth/Satellites_reveal_cause_of_Chamoli_disaster

4. Scientific highlights of Year 3

4.1 Q4-2021: Eastern Arctic historic velocities

The highlight of Q4 2021 was the submission of a first overarching study on historic datasets for the Eastern Arctic use case (Strozzi et al. 2022). Nearly complete mosaics of winter ice surface velocities for the 1990's over the Eastern Arctic (Novaya Zemlya, Franz-Josef-Land, Severnaya Zemlya and Svalbard) were compiled based on historical SAR data (JERS-1 and ERS-1/2) and compared to velocities derived from ALOS-1 PALSAR-1 (2008-2011) and Sentinel-1 (2020/21). For non-surging glaciers, the study revealed a clear acceleration of flow velocities in all regions (Fig. 11). For the surging glaciers in Svalbard a high variability in flow velocities was found. The dense time series available from Sentinel-1 since 2015 revealed a wide range of short-term and seasonal velocity fluctuations for both surging and non-surging glaciers (Fig. 12).

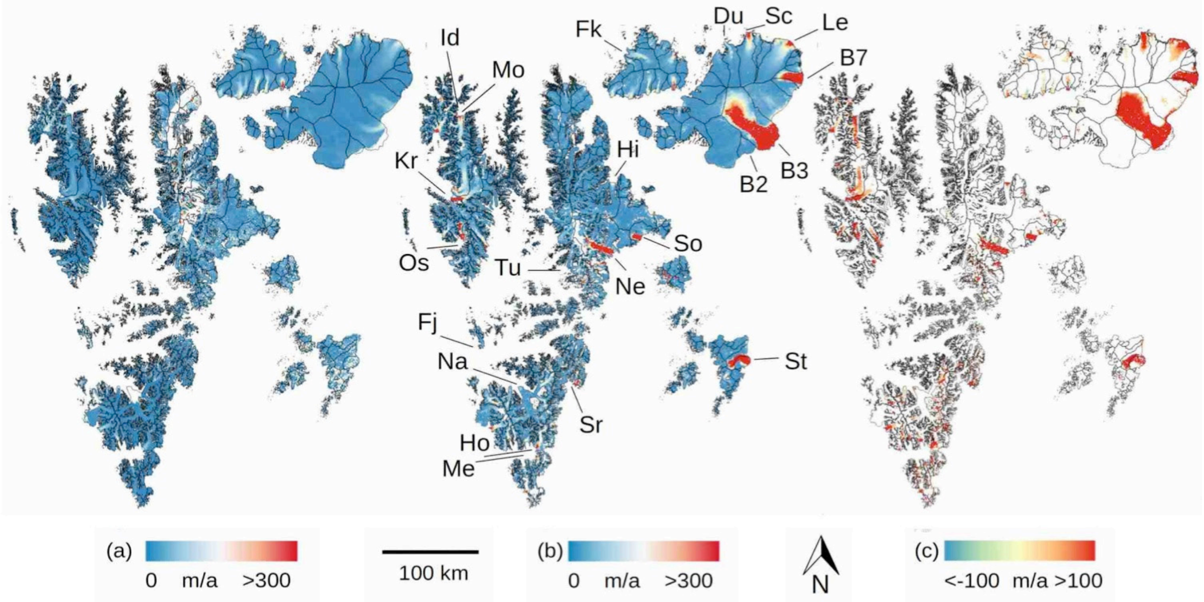


Fig. 11: Ice velocity maps for Svalbard: (a) ERS-1/2 1995.12.10-1995.01.29 & JERS1 1994.02.05-1998.03.26 & ERS-1 1992.01.03- 1992.01.15 and (b) Sentinel-1 2021.01.26-2021.02.12. (c) Difference map for areas with Sentinel-1 velocity >50 m/a. Glacier outlines between 2016 and 2018 (unpublished). Letters refer to glaciers mentioned in the text (Mo: Monacobreen; Id: Idabreen; Kr: Kronebreen; Os: Osbornbreen; Hi: Hinlopenbreen; Tu: Tunabreen; Ne: Negribreen; So: Sonklarbreen; Fj: Fridtjovbreen; Na: Nathorsbreen; Sr: Strongbreen; Ho: Hornbreen; Me: Mendelejevbreen; Fk: Franklinbreen; Du: Duvebreen; Sc: Schweigaardbreen; Le: Leighbreen; B2: Basin 2; B3: Basin 3; B7: Basin 7; St: Stonebreen).

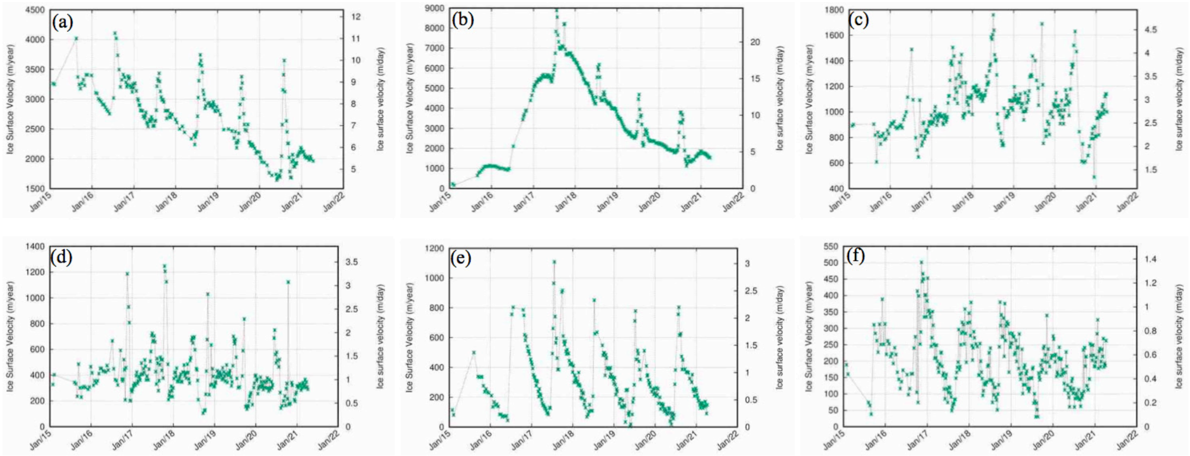


Fig. 12: Dense time series of Sentinel-1 velocities for glaciers in Svalbard. (a) Basin 3, (b) Negribreen, (c) Kronebreen, (d) Hornbreen, (e) Hinlopenbreen and (f) Idabreen.

4.2 Q1-2022: Glacier shrinkage in the Caucasus from 2000 to 2020

For Q1 2022 we have selected a study on glacier changes in the Caucasus from 2000 to 2020 as a scientific highlight (Tielidze et al. 2022). The study mapped glacier extents in 2000 from Landsat TM and ETM+ and in 2020 from Sentinel-2 and SPOTS 6/7 images. The glacier area decreased from 1381.5 to 1060.9 km^2, which is a reduction of 23.2% or -1.16% a^{-1}. Compared to previous inventories with reported area loss rates of -0.44% a^{-1} (1960-1986) and -0.49% a^{-1} (1986-2000) this is more than a doubling of the area loss rate. Fig. 13a shows area loss rates for different periods. The change rates were increasing towards smaller glaciers and thus more pronounced in the western and eastern Caucasus, hosting comparably smaller glaciers. In Fig. 13b we show an overlay of glacier outlines as digitized for different points in time. The year 2000 outlines will be used for RGI7 as they considerably improved the quality of the outlines in this region (Fig. 14). The study was the result of a joint effort by colleagues from Georgia, Russia and Switzerland.

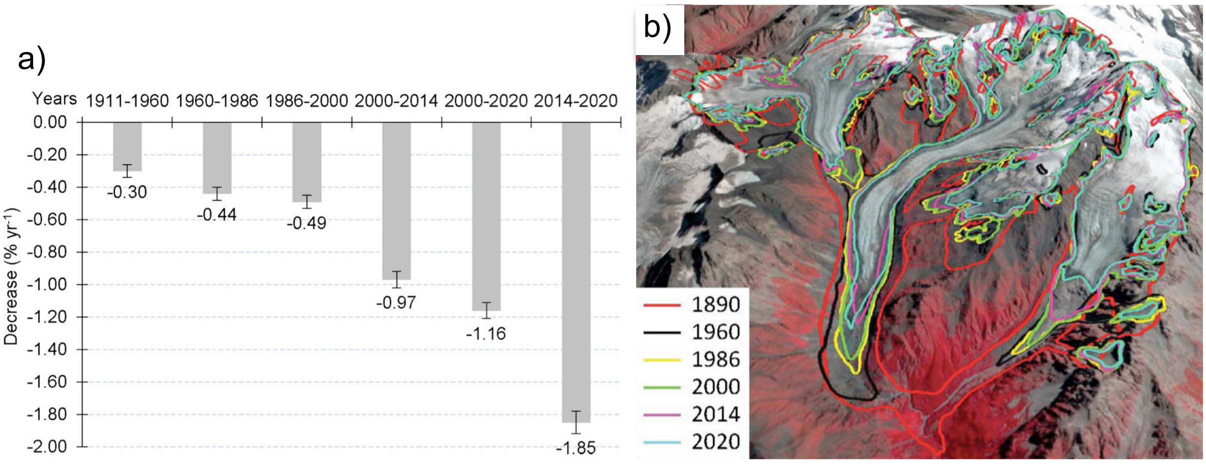


Fig. 13: a) Area change rates over different periods for glaciers in the Caucasus. b) Overlay of glacier outlines for different points in time for Tsaneri Glacier.

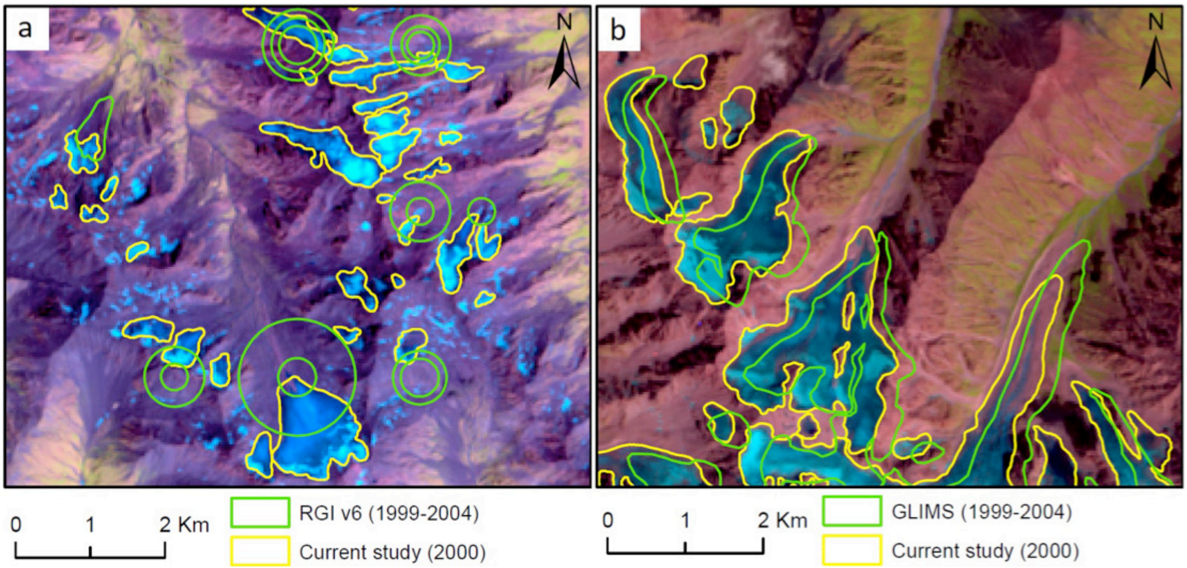
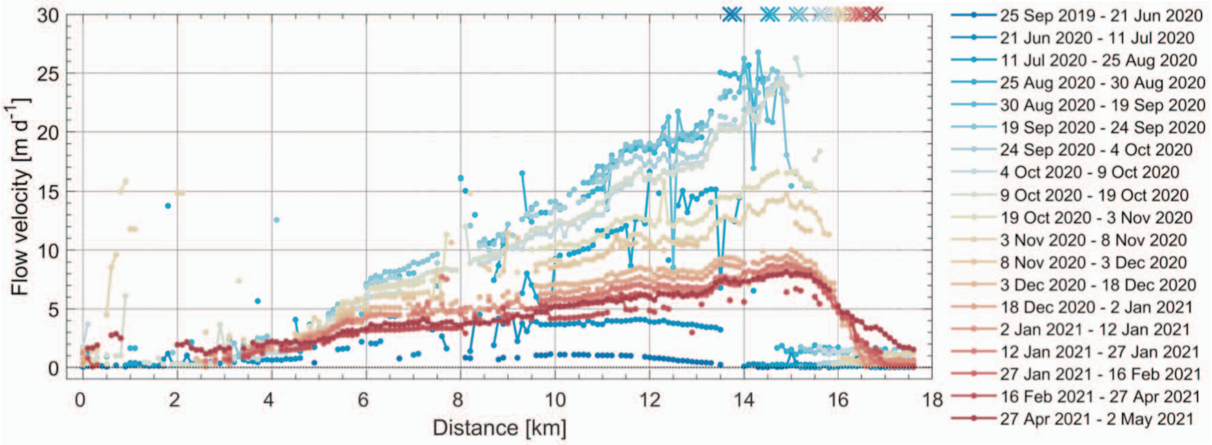


Fig. 14: Improvements from RGI6 (green outlines) to RGI7 (yellow). a) Replacement of nominal glaciers (green circles with an area equivalent to the size of a glacier), b) correction of a geo-location shift with the new inventory.

4.3 Q2-2022: Glacier surges in the Karakoram

For Q2 2022 we have selected our joint study on three glacier surges in the central Karakoram as a scientific highlight (Paul et al. 2022). The study used a wide range of satellite data (Landsat, Sentinel-1/2, Planet, TerraSar-X, ICESat-2) and DEMs (SRTM, HMA, SPOT) to obtain the densest possible time series of changes in glacier extent and elevation as well as velocity evolution to characterize the three very different surges. As an example, Fig. 15 shows the evolution of flow velocities along the centreline of South Chongtar glacier derived from Sentinel-2, reaching about 25 m/day in Sep 2020. We also intercompared results from different sensors (most of them agree very well) and tested their limits of applicability (e.g. Sentinel-1 failed to provide useful velocity data). The main science result is likely that the mechanisms driving a glacier surge can change over time, e.g. switch from a thermally to a hydrologically driven surge. Together with the supplement, the study contains in total 75 graphs / figures.



5. References

Haga, O., McNabb, R., Nuth, C., Altena, B., Schellenberger, T. and Kääb, A. (2020). From high friction zone to frontal collapse: Dynamics of an ongoing tidewater glacier surge, Negribreen, Svalbard. Journal of Glaciology, 66 (259), 742-754.

How, P., A. Messerli, E. Mätzler, M. Santoro, A. Wiesmann, R. Caduff, K. Langley, M.H. Bojesen, F. Paul, A. Kääb and J.L. Carrivick (2021): Greenland-wide inventory of ice marginal lakes using a multi-method approach. Scientific Reports, 11, 4481; doi.org/10.1038/s41598-021-83509-1.

Hugonnet R, McNabb R, Berthier E, Menounos B, Nuth C, Girod L, Farinotti D, Huss M, Dussaillant I, Brun F, Kääb A. (2021): Accelerated global glacier mass loss in the early twenty-first century. Nature, 592, 726-731; doi.org/10.1038/s41586-021-03436-z.

Paul, F. (2020): A 60-year chronology of glacier surges in the central Karakoram from the analysis of satellite image time-series. Geomorphology, 352, 106993; doi.org/10.1016/j.geomorph.2019.106993.

Paul, F., Piermattei, L., Treichler, D., Gilbert, L., Girod, L., Kääb, A., Libert, L., Nagler, T. Strozzi, T. and Wuite, J. (2022): Three different glacier surges at a spot: What satellites observe and what not. The Cryosphere, 16, 2505-2526; doi.org/10.5194/tc-16-2505-2022.

Kääb, A., Jacquemart, M., Gilbert, A., Leinss, S., Girod, L., Huggel, C., Falaschi, D., Ugalde, F., Petrakov, D., Chernomorets, S., Dokukin, M., Paul, F., Gascoin, S., Berthier, E. and Kargel, J. (2021): Sudden large-volume detachments of low-angle mountain glaciers - more frequent than thought. The Cryosphere, 15, 1751–1785; doi.org/10.5194/tc-15-1751-2021.

Strozzi, T., Wiesmann, A., Schellenberger, T., Kääb, A., and Paul, F. (2022): Long-term trends and seasonal variability of ice surface velocity in the Eastern Arctic from satellite SAR data. Earth System Science Data Discussions; doi.org/10.5194/essd-2022-44.

Tielidze, L. G., Nosenko, G. A., Khromova, T. E., and Paul, F. (2022): Strong acceleration of glacier area loss in the Greater Caucasus between 2000 and 2020. The Cryosphere, 16, 489-504.

Treichler, D., A. Kääb, N. Salzmann and C.-Y. Xu (2019): Recent glacier and lake changes in High Mountain Asia and their relation to precipitation changes. The Cryosphere, 13, 2977-3005.

Shugar, D.H. and 52 ohers (2021): A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. Science, 373, 300-306; doi.org/10.1126/science.abh4455.