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Climate Assessment Report (CAR)



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J **GAMMA REMOTE SENSING**





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1. Purpose

This is the Climate Assessment Report (CAR) of the Glaciers_cci+ Phase 2 project. It describes the products generated, their relevance and all outreach activities performed.

2. Introduction

The focus of the second Phase of Glaciers_cci+ (from Nov 2022 to Oct 2024) was on creating new, more experimental datasets and the intercomparison of sensor performance. The datasets (see CRDP) were thus created as demonstration products for technology testing (limits and possibilities of currently available sensors) or R&D applications rather than for user uptake, assessment and feedback. The latter activities are in the meantime implemented in the Copernicus Climate Change Service (C3S), at least for the glacier area and elevation/mass change products. Most of the nominal CAR contents requested in the SoW is about user feedback and assessment which is thus not really applicable to our work. However, the strong interaction of the Glaciers_cci+ team and its Climate Research Group (CRG) in Phase 2 will be demonstrated in this document by other means.

The first measure is our collaborative work in joint publications where all except one CRG member were involved and many new colleagues extended our spectrum of collaboration (e.g. on the topic ‘Tipping points in the Cryosphere’). A second point to mention in regard to the uptake of our work by others are our extensive outreach activities. They range from conferences and ESA success stories, to team events, summer schools and exhibitions attracting several ten thousand people. The third measure of the impact of our work on climate science and services is more indirect. Certainly also thanks to our work in Phase 2 of Glaciers_cci+, we were successful in bidding for one of the new ESA Climate Space X-ECV projects and the continuation of the C3S2 Cryosphere service. We also provided feedback to two important strategic ESA documents, where glaciers (and also snow cover and mountains) were only marginally considered before. Finally, the Oslo team received the ESA-EGU2023 Team Excellence award in recognition of their important work.

Overall, we are sure that the activities in Phase 2 of Glaciers_cci+ were of great value and significance for climate users and also that we provided important input for future improvements of products and sensors. In the following we provide an overview on the created datasets (Section 3) and some further details to the user-related outreach activities (Section 4). In the last Section 5 all Publications, conference contributions and outreach activities are systematically listed.

3. Datasets

In Table 1 we provide an overview of the larger datasets generated during Glaciers_cci Phase 2. Datasets created for sensor intercomparison or testing are not listed. The datasets are available from the Glaciers_cci server at Enveo (<http://glaciers-cci.enveo.at>).

Table 1: Overview of the generated datasets.

RGI	Region	Product	Year/Period	Sensor	Type	Remarks
	Global	Inventory	2017-2022	Sentinel-1	csv	Published by Kääb et al. (2023)
5	Greenland periphery	Elevation change	2016/19-2023, 2010-2023, 2018-2023	Sentinel-3A/B, Cryosat-2, ICESat-2	netCDF	different resolutions (500 m to 2 km) and coverage by each of the five datasets
14	Karakoram	Glacier surface classification	2016-2023 1994-2016	Sentinel-2 Landsat 5,7,8	netCDF	different resolutions (20 m for Sentinel-2, 30 m for Landsat) and coverage depending on satellite and track
14	Karakoram	Length change	1965, 1990s, 2000s, 2010s, 2020s	Corona KH4 Landsat 5,7, 8	csv	not made public (as quality was too low)

4. Assessment of the performed work

As mentioned above, the work performed and datasets generated were mostly related to R&D activities (e.g. sensor testing) and as such not directly of interest for a specific user group. However, we had nevertheless intense user interaction at a range of different levels. These are summarized in the following

4.1 Publications and conferences

For the joint publications (Berthier et al. 2023, Milkoreit et al. 2024, Piermattei et al. 2024, Winkelmann et al. 2024) we worked closely together with members of our CRG as well as several further colleagues. These collaborations can also be seen as an expression of the quality and usefulness of our work in Glaciers_cci. Two of our more topical publications (Kääb and Girod 2023, Kääb et al. 2023) were highlighted in special web features as success stories.

By convening or co-convening three sessions at large international conferences (EGU, IUGG, AOGS), we had additional opportunities for user interaction and exchange. For example, at the IUGG we included a discussion about research needs and challenges for the cryosphere of High Mountain Asia, which helped in shaping our proposal for the X-ECV activity.

4.2 Datasets

Our inventory of glacier surges was integrated in the latest version of the Randolph Glacier Inventory (RGI 7.0) that was released in 2023. Our dataset helped to have the most up-to-date information on glacier surges available for the community.



The elevation changes derived for Greenland's peripheral glaciers from various altimeters revealed that the DEM used for relocation of data points of Sentinel-3 has insufficient quality and should be replaced with a better version. This has been reported to the Sentinel-3 team.

The creation of the snow cover / glacier facies product reveals that there are some differences in the spectral reflectances of pixels covered by overlapping granules. This issue was identified for Sentinel-2 tiles and for Landsat scenes and is caused by the pre-processing of Level-1C data at ESA and USGS, which is performed on a tile basis. Such differences can disturb the quality of the mapping results in areas covered by more than one tile. It was thus decided to first merge the spectral top of atmosphere reflectances of overlapping tiles for an acquisition date and then continue with the further processing steps. Thus, glacier surface classification products are generated per Sentinel-2 track and Landsat path for the selected dates, considering the granules and rows, respectively, covering the area of interest.

The analysis of glacier length changes revealed that the best available multi-temporal dataset of glacier extents does not have the quality to be used for this purpose as many terminus positions were not or wrongly corrected. While the impact on glacier area changes derived in that study is likely small, length changes are seemingly much more critical. It was also clear that a ten-year time interval for glacier extent mapping is too long to capture the partly very fast and strong fluctuations. A five-year interval would be more appropriate, but difficult to realize with the available datasets.

Also the Glaciers_cci contribution to compile the year 2000 glacier inventories for New Zealand (Paul et al. 2023) and Baffin Island (together with C3S) were highly appreciated by the IACS working group in charge of RGI 7.0. The outlines helped to include and improve two important datasets for the global glacier inventory.

4.3 Outreach

Our team had also the opportunity to participate in a team building event for the support team of the CRISTAL mission. This event included a lecture about global glacier monitoring from the ground and space as well as three excursions to Pers and Mortratsch Glacier as well as to the Muragl rock glacier. On Pers Glacier we demonstrated how field-based mass balance measurements work and for Morteratsch we followed the illustrated path demonstrating glacier retreat over the past 175 years. The lecture and excursions were highly appreciated by the team and helped to see what CRISTAL might provide in regard to glacier observations.

The 'ESA Land Remote Sensing Advanced Course 2024 on Snow and Glaciers' was attended by 50 persons from PhD students to senior scientists. They learned the theoretical background in dedicated lectures and the practical part in hands-on exercises in a computer lab from the University of Innsbruck. The lecturers from the Glaciers_cci team (F. Paul and T. Nagler) received very positive feedbacks and smiling faces from the participants.

The contribution of (SAR) satellite images to the exhibition at the Henie Onstad Kunstsenter in Oslo provided a special form of access to our work for a large public. Along with the printed explanations provided at the installations, details of our work have become available for persons with a non-scientific background. Although a bit different from the standard distribution channels of our work, we think this exhibition was also a nice possibility to spread the word.



5. Outreach

Over the duration of Phase 2 of the Glaciers_cci+ project (2023-2024), consortium members have published 8 peer-review articles in 6 different journals and one report on Tipping Points. The team presented 14 talks or posters at national or international conferences (Section 5.2). Further outreach activities are listed in Section 5.3.

5.1 Peer-reviewed publications by the Glaciers_cci+ consortium

5.1.1. Journals

- Berthier, E.**, Floricioiu, D., Gardner, A.S., Gourmelen, N., Jakob, L., **Paul, F.**, **Treichler, D.**, Wouters, B., Belart, J., Dehecq, A., Dussaillant, I., Hugonnet, R., **Kääb, A.**, Krieger, L., Palsson, F., and **Zemp, M.** (2023): Measuring glacier mass changes from space - a review. Reports on Progress in Physics. 86, 036801, doi.org/10.1088/1361-6633/acaf8e
- Kääb, A.** and Girod, L. (2023): Brief communication: Rapid $\sim 335 \times 106 \text{ m}^3$ bed erosion after detachment of the Sedongpu Glacier (Tibet), The Cryosphere, 17, 2533–2541.
- Kääb, A.** and Røste, J. (2024): Rock glaciers across the United States predominantly accelerate coincident with rise in air temperatures. Nature Communications, 15, 7581; doi.org/10.1038/s41467-024-52093-z
- Kääb, A.**, Bazilova, V., Leclercq, P.W., Mannerfelt, E.S. and **Strozzi, T.** (2023): Global clustering of recent glacier surges from radar backscatter data, 2017–2022. J. Glaciol., doi.org/10.1017/jog.2023.35
- Milkoreit, M., E. Boyd, S.M. Constantino, V.H. Hausner, D. O Hessen, **A. Kääb**, D. McLaren, C. Nadeau, K. O'Brien, F.-J. Parmentier, R. Rotbarth, R. Rødven, **D. Treichler**, E. Wilson-Rowe and Y. Yamineva (2024): Governance for Earth system tipping points—A research agenda. Earth System Governance, 21, 100216.
- Paul, F.**, Baumann, S., Anderson, B, and **Rastner, P.** (2023): Deriving a year 2000 glacier inventory for New Zealand from the existing 2016 inventory. Annals of Glaciology, 90.
- Piermattei, L., Zemp, M., Sommer, C., Brun, F., Braun, M.H., **Andreassen, L.M.**, Belart, J. M. C., **Berthier, E.**, Bhattacharya, A., Boehm Vock, L., **Bolch, T.**, Dehecq, A., Dussaillant, I., Falaschi, D., Florentine, C., Floricioiu, D., Ginzler, C., Guillet, G., Hugonnet, R., Huss, M., **Kääb, A.**, King, O., Klug, C., Knuth, F., Krieger, L., La Frenierre, J., **McNabb, R.**, McNeil, C., Prinz, R., Sass, L., Seehaus, T., Shean, D., **Treichler, D.**, Wendt, A. and Yang, R. (2024): Observing glacier elevation changes from spaceborne optical and radar sensors – an inter-comparison experiment using ASTER and TanDEM-X data. The Cryosphere, 18, 3195-3230.
- Reinthaler, J. and **Paul, F.** (2024): Assessment of methods for reconstructing Little Ice Age glacier surfaces on the examples of Novaya Zemlya and the Swiss Alps. Geomorphology, 461, 109321, doi.org/10.1016/j.geomorph.2024.109321
- Colours: **Current** / **former** Glaciers_cci consortium, **CRG** members

5.1.2. Articles in reports

- Winkelmann, R., Steinert, N.J., McKay, D.I.A., Brovkin, V., **Kääb, A.**, Notz, D., Aksenov, Y., Arndt, S., Bathiany, S., Burke, E., Garbe, J., Gasson, E., Goelzer, H., Hugelius, G., Klose, A.K., Langebroek, P., **Marzeion, B.**, Maussion, F., Nitzbon, J., Robinson, A., Rynders, S., Sudakow, I. (2023): Tipping points in the cryosphere. - In: Lenton, T.M. et al. (Eds.). The Global Tipping Points Report 2023, Exeter, University of Exeter, pp. 56-77.



5.2 Presentations at conferences, meetings and workshops

EGU General Assembly 2023, Vienna (24.-28.4.2022)

A. Käab & L. Girod: 'Rapid and massive 335 million m³ glacier bed erosion after de-tachment of the Sedongpu Glacier (Tibet)'

M. Zemp et al.: 'Insights into and findings from global datasets on glacier distribution and changes'

ESA-EGU 2023 Excellence Award: A. Käab and S. Winsvold presented a condensed summary of the work of the Oslo team (incl. D. Treichler, B. Altena and L. Girod)

IUGG General Assembly, Berlin (12.-16.7.2023)

F. Paul et al.: Convener for Session C02: 'Glacier changes in High Mountain Asia and the Karakoram Anomaly: Latest insights from the atmosphere and cryosphere'

F. Paul & F. Goerlich: 'Two glacier surges in the central Karakorum observed from Corona stereo images'

CRISTAL Team Event, Pontresina (27.-30.9.2023)

F. Paul: 'Glacier monitoring: From the field to the space and back'

EC/ESA Earth Systems Science Initiative meeting, ESRIN Frascati (22.-24.11.2023)

F. Paul: 'Glaciers_cci, AlpGlacier and C3S'

Deutsche Meteorologische Gesellschaft, Seewetteramt Hamburg (9.1.2024)

F. Paul: 'Globaler Gletscherschwund: Was wir wissen und was nicht'.

WMO Panel on Polar and High Mountain Observations, Research and Services (PHORS), Oslo (13.2.2024)

A. Käab: 'Tipping Points in the Cryosphere'.

EGU General Assembly, Vienna (24.-28.4.2023)

F. Paul: Convener of the session: 'Observing and measuring glacier changes from the Little Ice Age to the present based on in situ and remote sensing data'

F. Paul, P. Rastner: 'Glacier area changes on Baffin Island from 2000 to 2019 derived from Landsat and Sentinel-2 satellite images' (jointly with C3S)

EODC Forum 2024, Vienna (10.-11. June 2024)

G. Schwaizer and T. Nagler presented ENVEO's cryosphere products and services, including inter alia the glacier ice velocity and the glacier surface classification products

AOGS (Asia Oceania Geosciences Society), Peyongchang, South Korea (24.-28.6.2024)

F. Paul, Co-convener of session IG16 'Advancements in Cryospheric Studies of Central Asia: Bridging Knowledge Gaps and Fostering Regional Collaboration'

European Polar Science Week, Copenhagen (3.-6.9.2024)

F. Paul: 'Some results from Glaciers_cci+ Phase 2' (online contribution)

13th ESA Land Remote Sensing Advanced Course 2024, Innsbruck (16.-20-9-2024)

F. Paul: 'Glacier mapping with multispectral satellite data' (lecture and exercise)

T. Nagler: 'SAR-based methods for snow cover and SWE' (lecture)

T. Nagler: 'Snowmelt area and wetness (based on SAR)' (lecture and exercises)

CCI Co-location Meeting, ECSAT Harwell (16.-18.10.2024)

F. Paul et al.: 'Scientific highlights of the Glaciers_cci project: Year 2'

5.3 Further outreach activities and services

5.3.1. Teaching (ESA Land Remote Sensing Advanced Course 2024)

F. Paul and T. Nagler guided 50 students through practical exercises (hands on computer work) focussed on mapping of glacier extents from optical and of snow melt from SAR data.

5.3.2. ESA Webstories and news items

Mapping of glacier surges globally with Sentinel-1:

<https://sentinels.copernicus.eu/fin/web/success-stories/-/glacier-surges-mapped-globally-from-space>

Repeat ice and rock avalanches observed from space:

<https://sentinel.esa.int/web/success-stories/-/huge-mountain-erosion-event-witnessed-from-space>

5.3.3. Further outreach activities

CRISTAL Team Event, Pontresina (27.-30.9.2023)

F. Paul: Field guide for excursions to Diavolezza, Morteratsch Glacier and Val Muragl

J. Reinthaler: Field guide to Pers Glacier, incl. drilling exercise for ablation stakes

Exhibition of glacier images, Oslo (2023)

The Oslo team contributed satellite images from Svalbard to an art installation by Lesia Vasylchenko named 'Sensing the Near Real Time (SNRT)' that was presented at the exhibition 'New Visions' of the Henie Onstad Triennial for photography and new media (Photo below). The exhibition attracted 80,000 guests.

5.3.4. Services

Feedback to ESA by T. Nagler and F. Paul to the 'ESA Earth Observation Science Strategy Foundation Study, D2 v3' and 'Earth Science in Action for Tomorrow's World Earth Observation Science Strategy 2040' draft documents. Before, snow cover, glaciers and mountain ranges were not well represented in these documents.



Photo from the exhibition in Oslo with A- Kääh (left) and D. Treichler (right).