ESA Climate Change Initiative (CCI+)
Essential Climate Variable (ECV)
Greenland_Ice_Sheet_cci+ (GIS_cci+)

Final Report (FR)

Prime & Science Lead: Louise Sandberg Sørensen

DTU Space, Copenhagen, Denmark

Technical Officer: Anna Maria Trofaier

ESA ECSAT, Didcot, United Kingdom

Consortium:

Asiaq Greenland Survey (ASIAQ)

DTU-Space, Department of Geodynamics (DTU-S)

DTU-Space, Department of Microwaves and Remote Sensing (DTU-N)

Danish Meteorological Institute (DMI)

ENVironmental Earth Observation IT GmbH (ENVEO)

Science [&] Technology AS (S&T)

Technische Universität Dresden (TUDr)

The Geological Survey of Denmark and Greenland (GEUS)

The Niels Bohr Institute (NBI)

Northumbria University (NU)

University of Leeds (UL)

Signatures page

Prepared by	Louise Sandberg Sørensen Science Leader, DTU	Digitally signed by Louise Sandberg Sørensen Date: 2025.01.15 11:40:00 +01'00'
Issued by	Daniele Fantin Project Manager, S[&]T	Digitally signed by Daniele Fantin Date: 2025.01.08 12:55:32 CET
Checked by	Louise Sørensen Science Leader, DTU	
Approved by	Anna Maria Trofaier Technical Officer, ESA	Digitally signed by Anna Maria Trofaier Date: 2025.01.15 10:33:23 Z

Table of Contents

Change Log

Issue	Author	Affected Section	Reason	Status
0.5	D. Fantin	All	Document Creation	
1.0	Louise Sørensen	All. This is a new document. Does not build on previous deliverables	Released to ESA	

Acronyms

Acronyms	Explanation
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CFL	Calving Front Location
CS2	CryoSat-2
DEM	Digital Elevation Model
DMI	Danish Meteorological Institute
DTU-N	DTU Microwaves and Remote Sensing Group
DTU-S	DTU Geodynamics Group
ECV	Essential Climate Variable
ENVEO	ENVironmental Earth Observation IT GmbH
EO	Earth Observation
ESA	European Space Agency
GCOS	Global Climate Observation System
GEUS	Geological Survey of Denmark and Greenland
GFZ	Deutsche GeoForschungsZentrum
GIS	Greenland Ice Sheet
GLL	Grounding Line Location
GMB	Gravimetry Mass Balance
IMBIE	Ice Sheet Mass Balance Inter-Comparison Exercise
InSAR	Interferometric Synthetic Aperture Radar
IV	Ice Velocity
MEaSUREs	Making Earth System Data Records for Use in Research Environments (NASA)
MFID	Mass Flux and Ice Discharge
NBI	Niels Bohr Institute, University of Copenhagen
NEGIS	North East Greenland Ice Stream
OptIV	Optical IV
OT	Offset Tracking
PROMICE	Danish Program for Monitoring of the Greenland Ice Sheet
RA	Radar Altimetry
S&T	Science and Technology AS
S2	Sentinel-2
SAR	Synthetic Aperture Radar
SEC	Surface Elevation Change
SMB	Surface Mass Balance
SoW	Statement of Work
TPROP	Technical Proposal
TUDr	Technische Universität Dresden
UL	University of Leeds
URD	User Requirement Document

1. Introduction

This document is the Final Report (FR) prepared for Phase 2 of the Greenland_Ice_Sheet_cci+ GIS_cci+ project in accordance with the Contract [AD-1] and the Statements of Work (SoW) [AD-2] with Annex B.

The purpose of the document is to summarize the activities performed during the project. We briefly present the user requirements, the targets for the product development, the algorithm development and the outcome for each of the parameters: SEC, IV, GMB, MFID and SGL. We further provide some recommendations for future work, based on our experience in the current phase of the project, including our validation activities. In the last section, we highlight some of the outcomes of the Climate Assessment Report (CAR [RD-6]) and the User Workshop Report (UWR [RD-7]) based on a user workshop and questionnaire carried out in September 2024.

1.1 Document Structure

This document is structured as follows:

- Chapter 1 introduces the document.
- Chapter 2 provides short descriptions of activities performed during the project, focusing on the user requirement analysis and algorithm development for each ECV parameter.
- Chapter 3 lists the data products released.
- Chapter 4 lists the outreach performed in terms of publications.
- Chapter 5 provides a short summary with final conclusions
- Chapter 6 lists references.

1.2 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD-1	ESA/Contract No. 4000126523/19/I-NB - Greenland_Ice-Sheets_CCI+ and its Appendix 1 (incl CCN3)	CCI+ Phase 1 New R&D pm CCI ECVs for Greenland _Ice Sheet_cci (incl CCN3)	Cont: 2019.03.06 CCN3: 2022.12.05	-
AD-2	ESA-EOP-SC-AMT-2021-53	Climate Change Initiative Extension (CCI+) Phase 2 - New R&D on CCI Essential Climate Variables -SoW (incl Annexes)	2022.06.10	Issue 1 Revision 2

Table 1.2: List of Reference Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
RD-1	DTU-ESA-GISCCI+-URD-001	User Requirements Document (URD)	05/07/2023	3.1
RD-2	DTU-ESA-GISCCI+-ATBD-001	Algorithm Theoretical Basis Document (ATBD)	25/11/2024	2.1
RD-3	DTU-ESA-GISCCI+-PVP-001	Product Validation Plan (PVP)	01/12/2023	3.0

RD-4	DTU-ESA-GISCCI+-PVIR-002	Product Validation and Intercomparison Report (PVIR)	18/12/2024	1.0
RD-5	DTU-ESA-GISCCI+-PUG-001	Product User Guide (PUG)	18/12/2024	3.1
RD-6	DTU-ESA-GISCCI+-CAR-002	Climate Assessment Report (CAR)	20/12/2024	1.0
RD-7	DTU-ESA-GISCCI+-UWR-001	User Workshop Report (UWR)	18/12/2024	3.1
RD-8	DTU-ESA-GISCCI+-CRDP_RN-001	CRDP Release Note (CRDP RN)	30/09/2024	1.0

Note: If not provided, the reference applies to the latest released Issue/Revision/Version

2. Activities Performed

2.1. User requirements analysis

Immediately before the beginning of the CCI+ GIS phase 2, new GCOS requirements were published. These were discussed in the user requirement analysis and described in URD v. 3.1 [RD-1]. Table 2.1 shows the user needs for ice sheet-related requirements from GCOS (2022). Here the following definitions apply: Goal (G): an ideal requirement above which further improvements are not necessary. Breakthrough (B): an intermediate level between threshold and goal which, if achieved, would result in a significant improvement for the targeted application. Threshold (T): the minimum requirement to be met to ensure that data are useful.

ECV Product	Temporal Resolution[1]	Horizontal Resolution	Required Measurement Uncertainty[2]	Stability[3]
Surface elevation change	(G) 1 month (B) - (T) 12 months	(G) - (B) - (T) 100m	(G) - (B) - (T) 0.1m/year[4]	(G) - (B) - (T) 0.1m/year
Ice Velocity	(G) 1 month (B) - (T) 12 months	(G) 50m (B) 100m (T) 1000m	(G) 10 (B) 30 (T) 100m/year[4]	(G) - (B) - (T) 10m/year[6]
Ice Volume Change	(G) 30 days (B) - (T) 365 days	(G) - (B) - (T) 50m	(G) - (B) - (T) 10 Gt/year[4,5]	(G) - (B) - (T) 1 Gt/year[5]
Grounding Line Location and Thickness	(G) - (B) - (T) 1 year	(G) 100m (B) - (T) 1000m	(G) - (B) - (T) 1m	(G) - (B) - (T) 1m

Table 2.1: New ice sheet requirements from GCOS.

In the URD we discussed how these new GCOS ECVs are not perfectly aligned with the CCI+ GIS since e.g. mass changes are no longer identified as an ECV, while volume change is introduced. This does not ideally align with the GMB and MFID data products currently in our portfolio. We find that the project has growing interest and download rates for its data products, suggesting broad utility across multiple domains.

Based on the above requirements together with data availability and processing capabilities we defined the products to be derived in the current phase; see Table 2.2.

ECV product	Spatial resolution	Temporal resolution	Period for cci/cci+	Satellite/other data & Regions for CCI+
SEC	5 km	1 year (Greenland-wide)	1992-2021 (*) 2022-2024 (CCI+-P2)	ERS-1/2, ENVISAT, CryoSat-2, Sentinel-3A/B. Greenland-wide, updated annually. 2 and 5-year means. New: sub-annual elevation changes ice sheet wide.
IV	250 m (OT) 100m (InSAR) 100m (OptIV)	1 year (Greenland-wide) 6/12-day (Margins, selected areas) Summer Season (Variable temporal resolution).	2014-2017 (*) (OT) 2017-2024 (C3S) (OT) 2018-2021 (*) (InSAR) (Greenland-wide) Since Oct 2014 (*) Since Oct 2014 (CCI+-P2) (Margins) 2016, 2019-2021 (*) 2022-2024 (CCI+-P2) (key ice streams)	Sentinel-1A/B, SAOCOM-1A/B, (SAR), Sentinel-2 (optical). All Greenland on yearly basis. All margin zone is available through *CryoPortal*. 1992-2024 products are available through the CCI and *PROMICE* data portals. Optical IV data over 9 key ice streams from Sentinel-2.
GMB	50 km	Monthly	2002-2021 (*) (data gap 2017-18) 2022-2024 (CCI+-P2)	GRACE-FO, GRACE. Greenland-wide and Zwally drainage basins.
MFID (#)	N/A (200m internal grid spacing)	Monthly (across basins)	2014-2021 (*) 2014-2024 (CCI+-P2) (Select ice streams)	IV data from Sentinel-1-A/B. Ice thickness data & ice mask from BedMachine_v5, surface elevation from PRODEM (CCI+-P2) Data for 9 major outlet glaciers.
SGL	10 m 10 m	Monthly (Select areas) Monthly (Select areas)	2019 (*) (outlines) 2019 (CCI+-P2) (volume)	Sentinel-2 optical data. Landsat-8 used for validation, ArcticDEM used for sink detection. (Experimental ECV product) Two select regions: Nioghalvfjerds-bræ and Zachariæ Isstrøm

Table 2.2: Overview of data product targets for CCI+ GIS phase 2. Taken from URD.

To succeed with the defined products to be generated (Table 2.2) we have carried out R&D to improve algorithms for all of our data products. In the following, these algorithm improvements for each of the data products are briefly outlined (see details in ATBD v2.1 [RD-2]). Based on the extensive validation activities (described in detail in PVP v3.0 [RD-3] final and PVIR v. [RD-4]), some suggested improvements for the individual products were also provided. We highlight a few of these also in the following sections.

We have updated the Product User Guide to include product updates and user guides for new products (see PUG v.3.1 [RD-5]).

In the following sections, we briefly describe the algorithm development and the outcome for each of the parameters: SEC, IV, GMB, MFID and SGL. We further provide some recommendations for future work, based on our experience in the current phase of the project, including our validation activities.

2.2. Surface elevation change

To meet the new GCOS requirements of monthly SEC, a completely new algorithm had to be developed, since our legacy SEC is derived from an algorithm which outputs multi-year trends in elevation. It was not initially evident that the developed method would indeed be capable of delivering monthly estimates, hence the target was set for annual. The new algorithm (for the new product called dSEC) is based on a state-space model. Satellite data are only available along satellite tracks, leading to irregularly distributed data and gaps between tracks. The new dSEC method addresses these gaps by utilizing elevation knowledge from previous time steps or nearby data points. Temporal correlations are addressed using an Autoregressive model of order 1 (AR1) process. This component captures the autocorrelation between observations at different time steps, providing a more accurate representation of temporal patterns in surface elevation changes.

This dSEC algorithm outputs a dataset capable of revealing the spatial pattern over the Greenland Ice Sheet every month or generating a time series at all grid points (See Fig 2.1). An additional strength is that it also provides an estimate of the errors, which is controlled by input data uncertainty and distance (in time and space) between predicted points and the input data.

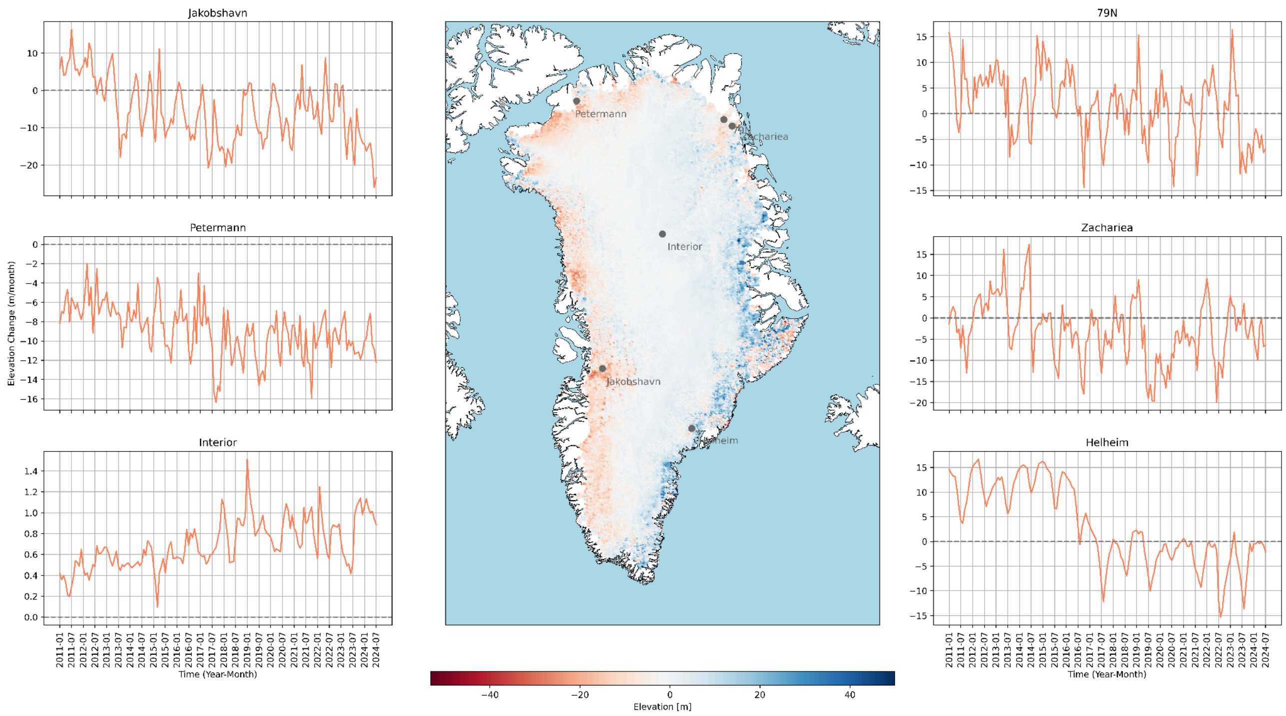


Figure 2.1: The map in the middle shows the surface elevation changes over the GrIS over one month. On the map are five glaciers and one centre point marked in grey. The time series for these glaciers have been plotted on the sides.

Based on the work carried out in CCI+ GIS phase 2, some selected recommendations for future work on SEC products are:

- Investigation of the use of RA datasets that rely on retracking that is tuned for tracking the actual air-snow surface. This is especially relevant for the SEC products.
- An improvement to the dSEC product would be to provide it with a range of spatial and temporal resolutions. This flexibility would enable easier intercomparisons with the validation data across different scales and timeframes.
- Another potential dSEC product improvement would be to derive the spatial component using a triangular grid instead of the current regular grid. This approach would not only enhance processing speed but also provide greater flexibility in representing irregular boundaries and topographies.
- Additionally, allowing a few more iterations with weighted adjustments in the model would significantly help minimize the impact of outliers on the results.

2.3. Ice Velocity (IV)

In the current phase of the project, some processing tools have been developed and implemented for using SAOCOM L-Band SAR data, also in synergy with Sentinel-1, for optimizing the ice velocity retrieval on the Greenland Ice Sheet. Adaptation of the existing IV processing chain for SAOCOM data focused on handling the larger baselines and automatization of co-registration of SAOCOM data, by combining orbital data, a DEM and refinement using local matching, which is needed due to the reduced quality of the orbital state vectors. For this refinement, a long-term averaged ice velocity map derived from Sentinel-1 offset tracking is used. Tools have also been developed for combining crossing orbits (ascending/descending) from SAOCOM and Sentinel-1 for InSAR IV retrieval. In addition, the existing processing line for Sentinel-1, developed in an earlier phase of the project, was used to continue the generation of ice velocity maps covering the Greenland Ice Sheet margins at 12-day intervals extending the time series to the present.

The new InSAR Line-of-sight (LoS) velocity product that has been produced in the current phase of the project is based on intermediate products generated during the InSAR velocity processing. The geocoded LoS velocity maps from several acquisitions on the same track are then stacked to form a time series, and the pixel-wise median of the time series is subtracted, such that the output product is the LoS velocity anomaly, which can reveal small-scale rapid variations. This approach was implemented in CCI+ GIS phase 2 to generate a prototype data product that can be utilized to study e.g. related to e.g. subglacial hydrological phenomena, as described in (Andersen, 2023).

In addition to the InSAR Line-of-sight velocity product, the project also produces optical IV products (Opt-IV) using S2 images. This derives the pixel shift between two S2 images at different times through feature tracking to track the ice velocity. This process works by identifying and matching distinct surface features, such as crevasses or other patterns, in two Sentinel-2 images taken at different times. By measuring how far these features have moved between the two images, the method calculates the speed and direction of the ice flow over the given time period.

During this phase, the feature tracking algorithm in the IV processor was upgraded, so instead of using only the blue band, the feature tracking uses four bands to better spot the features of the glaciers. Also, the post-processing has been improved with a speckle algorithm that helps filter and smooth the IV product.

Some selected recommendations for future work on IV products are:

- Use the new Sentinel-1 Extended Timing Annotation Dataset (ETAD) product.

  ETAD corrects for the tropospheric and ionospheric path delays, the tidal-based surface displacements (solid-earth tide), and SAR processing effects. The correction can enhance the absolute geolocation accuracy of the SAR images and the relative collocation accuracy of repeat pass image stacks, which can improve the ice velocity estimation.

- 3D Ice Velocity

  Observations of the 3D ice velocity field are important for studies of glacier hydraulics, and for modelling the dynamic response of glaciers to changing boundary conditions. By utilizing (incoherent) offset tracking on SAR amplitude images of crossing (ascending/descending) orbits it is possible to retrieve detailed 3D surface displacements. In contrast to the conventional technique for ice motion mapping which assumes surface-parallel flow, this method delivers the true velocity vector.

- Double-difference InSAR (DDInSAR) for identifying uplift events

  The current uplift product is a byproduct of the IV InSAR chain, and as such based on the processing of time series of large images with a full InSAR stack (phase unwrapping and calibration), from which a median LoS velocity is calculated and subtracted from the individual measurements, removing the bulk of the horizontal flow contribution to the line-of-sight velocity. Double-difference InSAR, instead, has the potential to reveal uplift events directly from the wrapped DDInSAR phase from a single InSAR triplet, without the added complexity of unwrapping calibration and processing of the full-time series. This allows much faster screening of potential uplift events, and also the identification of events in areas impacted by phase unwrapping errors in the current product. After identification with DDInSAR, smaller areas with identified events can then be full-stack processed in a targeted fashion.

- Refinement of Feature Tracking

  Improving the weighting of pixel pairs and velocity calculation methods can enhance the accuracy of ice velocity measurements derived from Sentinel-2 images.

- Coregistration Improvements

  The current reliance on coastal features for coregistration limits the analysis of inland glaciers. A proposed solution is to use neighbouring tiles with visible coastlines as reference points, enabling better coregistration for large, inland glaciers. This would expand the applicability of the CCI IV algorithm to previously unsupported regions.

- Floating Ice Filtering

  Implement a postprocessing step using pre-calculated Calving Front Locations (CFL). By filtering out measurements beyond the CFL, the algorithm can reduce erroneous data caused by floating ice.

2.4. Gravimetric Mass Balance (GMB)

For the GMB algorithm improvement in the CCI+ GIS phase 2, TUD implemented an ellipsoidal correction to make the inference of ice mass changes from gravity field changes more accurate, because recent research has highlighted some limitations of the spherical approximation applied so far (Chao 2016, Li et al. 2017; Ditmar et al. 2018; Ghobadi-Far et al. 2019). Two approaches for the correction have been implemented and assessed: The correction proposed by Ghobadi-Far et al. (2019) which explicitly converts the spherical harmonic coefficients to ellipsoidal harmonic coefficients and the correction proposed by Ditmar et al. (2018) which applies correction factors for each point of interest. Both corrections showed similar results and the correction by Ditmar et al. (2018) with correction factors computed for each cell of the 50 km x 50 km grid has been implemented for the CCI+ GIS phase 2 GMB product. Fig 2.2 shows the impact of the product update on the time series. Additionally, the Level-2 spherical harmonic product has been updated from CSR-RL06 to CSR-RL06.2, resulting in a slight noise reduction for the GRACE-FO months.

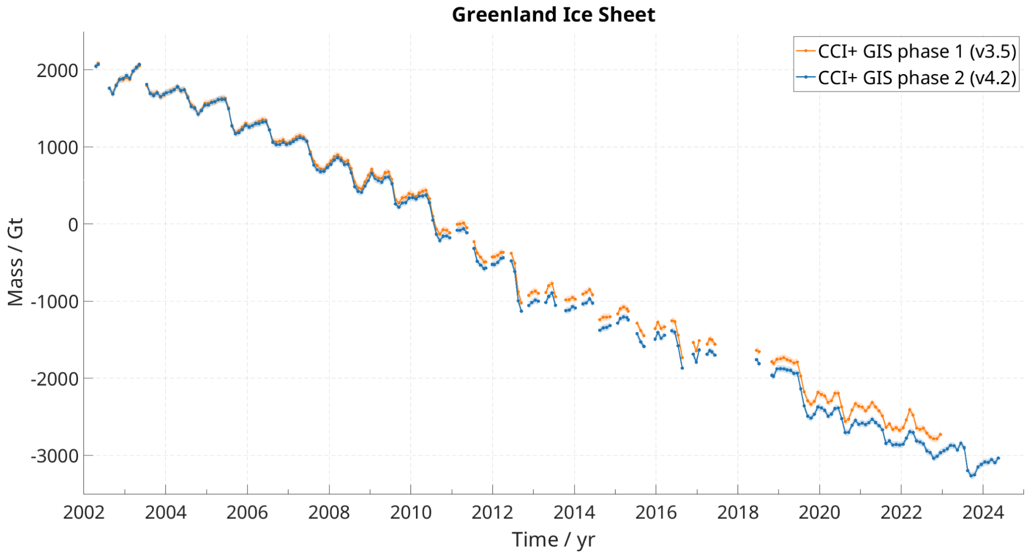


Figure 2.2: Resulting mass change time series for the Greenland Ice Sheet for the last and the new GMB product. Notice the trend difference due to the ellipsoidal correction and the slight noise reduction over the GRACE-FO months due to the Level-2 data update.

A portion of the mass change observed by GRACE and estimated in the GMB is caused by the glacial isostatic adjustment (GIA), a movement of the crust and the mantle as a rebound from the last ice age. As discussed in Barletta et al. (2013), such a component accounts for a trend between -6 to +10 Gt/yr, which represents a large part of the uncertainty in the GMB estimate. After careful analysis and comparison (Berg et al 2023, Barletta et al 2024) with the observed uplift rates measured by the GNSS network in Greenland (GNET), we conclude that our GIA model knowledge on Greenland has a fundamental component missing that possibly comes from the rebound caused by recent deglaciation such as little ice age (LIA). Nevertheless, we found (Berg et al 2023) that one GIA model among others is slightly more compatible with GNSS uplift residuals, that is the LM17.3 (Steffen et al 2021). However, such a model does not have a consistent global component, while the GIA currently in use for the GMB, the Caron et al. (2018), is global and consolidated. The Caron et al 2018 and LM17.3 give a correction of about +7.49 and +2.72 Gt/yr respectively, and the difference is less than 2% of the total GMB trend of -252 Gt/yr (2002-2024). Since, for now, no GIA model for Greenland is correct, for the above-mentioned other reason we decided to keep using the Caron et al. (2018), while waiting for new GIA models to be studied and developed for Greenland. The two studies (Berg et al 2023, Barletta et al 2024) carried out within this CCI phase 2, provide strong motivations for the ongoing renovated studies on GIA in Greenland.

The new GRACE-FO mission, besides the K-Band Ranging (KBR) instrument, also has a Laser Ranging Instrument (LRI) on board. We tested the data obtained with the LRI and our conclusion is that not much can be gained from the higher accuracy in the range measurements. One of the main reasons is the issue with the accelerometers on one of the satellites. Other reasons are the background models. Both factors are dominating the uncertainties.

For future improvement of the GMB, we recommend

1) To improve the error characterization on both the time series and the trend grids.
2) To include other data (e.g. GMB from GNET, Barletta et al 2024) to close the gap and improve the accuracy of the existing estimates.

2.5. Mass Flow Rate and Ice Discharge (MFID)

In the updated CCI+ Phase 2 version of MFID, the baseline thickness is determined from the basal topography model BedMachine v5 (Morlighem et al., 2017) and the 2019 surface elevation from PRODEM (Winstrup et al., 2024), with the thickness changes determined from the SEC ECV product. The major contributor to changes in MFID comes from ice flow change which is provided by the IV ECV. While changes in ice flow velocity are the largest contributor to changes in MFID, the thickness is the largest contributor to uncertainties in the total MFID. The current version of the algorithm now calculates flux changes based on thickness calculated from annual DEMs. This change gives a higher control over the thickness, thickness changes and errors.

As part of the algorithm update, the impact of using annual elevation changes instead of 5-year averages was assessed. This was done by running the algorithm over the entire period using the 5-year averages and then repeating the process with annual elevation changes incorporated from 2019 onward. The resulting differences between the two runs are illustrated in Figure 2.3. The total discrepancy amounts to approximately 5 Gt/year, equivalent to about 1% of the total discharge. We note here that the new product produced in CCI+ GIS phase 2 exceeds the target as indicated in Table 2.2, since the product includes the entire ice sheet and not just selected glaciers.

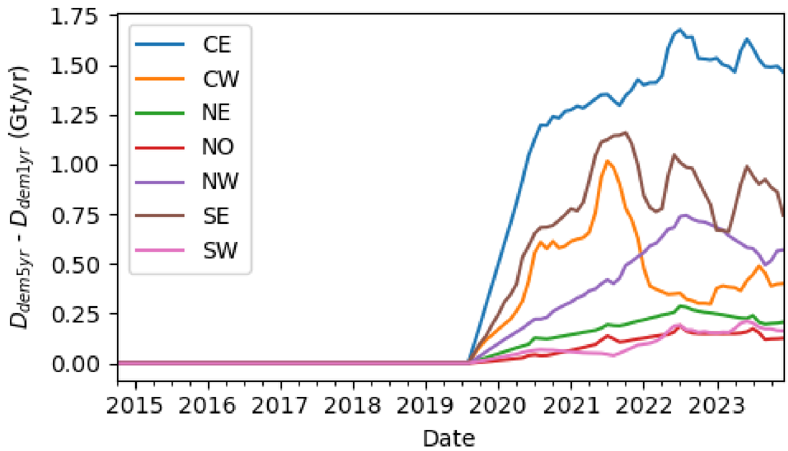


Figure 2.3: The difference in MFID between annual varying DEMs from 2019 or 5-year averages.

Based on the work carried out in CCI+ GIS phase 2, some selected recommendations for future work on MFID products are:

- Update the MFID processor to include the new dSEC product, which has monthly resolution so that the temporal resolution of IV and SEC are the same.
- Update gate positions and all data to the newest available versions.

2.6. Subglacial lakes (SGL)

The Greenland ice sheet is melting at an increasing rate. As a result, the area over which the ice sheet experiences melt is also expanding, and the melt of the ice sheet generates large lakes on the surface of the Greenland ice sheet, which eventually drain through the ice sheet hydrologic system (surface drainage stream, moulins, and sub-glacial streams to the surrounding fjords).

Supraglacial lakes are an important parameter for understanding the current and future state of the Greenland Ice Sheet. Previous studies have focused on mapping supraglacial lake extent using optical and radar imagery, while lake depth is more difficult to estimate due to the sparse temporal and spatial coverage of laser altimeters such as ICESat-2. The Supraglacial Lakes (SGL) experimental product S&T is developing is based on a supervised deep-learning approach to predict lake extent and depth based on the subtle spectral signatures acquired from Sentinel2 imagery. The model is trained on an existing lake extent product and elevation profiles derived from ICESat-2 across 40 individual lakes. This data consists of roughly 14k data points that form transection lines across lakes, of which approx 4k are from the IS2 strong beam, and the remaining 10k are from the weak beam.

The output of this approach is a proof-of-concept study whereby deep learning can utilise contextual information from the input image to produce a lake depth and extent prediction. Preliminary results indicated that the methodology is feasible and that the output model successfully produced a reasonable lake extent and depth prediction despite data limitations.

The Supraglacial Lakes (SGL) experimental product was generated for two “hot-spot” glaciers, the Nioghalvfjerdsbræ and Sermeq Kujalleq (hereafter 79°N and SK, respectively) for the 2019 summer melt season (May to October).

Preliminary results (Figure 2.4) have been presented at the Global Space Conference on climate change 2023 (GLOC 2023), which was held in Oslo, Norway on 23-25 May 2023, and published in the peer-reviewed conference proceeding (Robinson et. al., 2023)

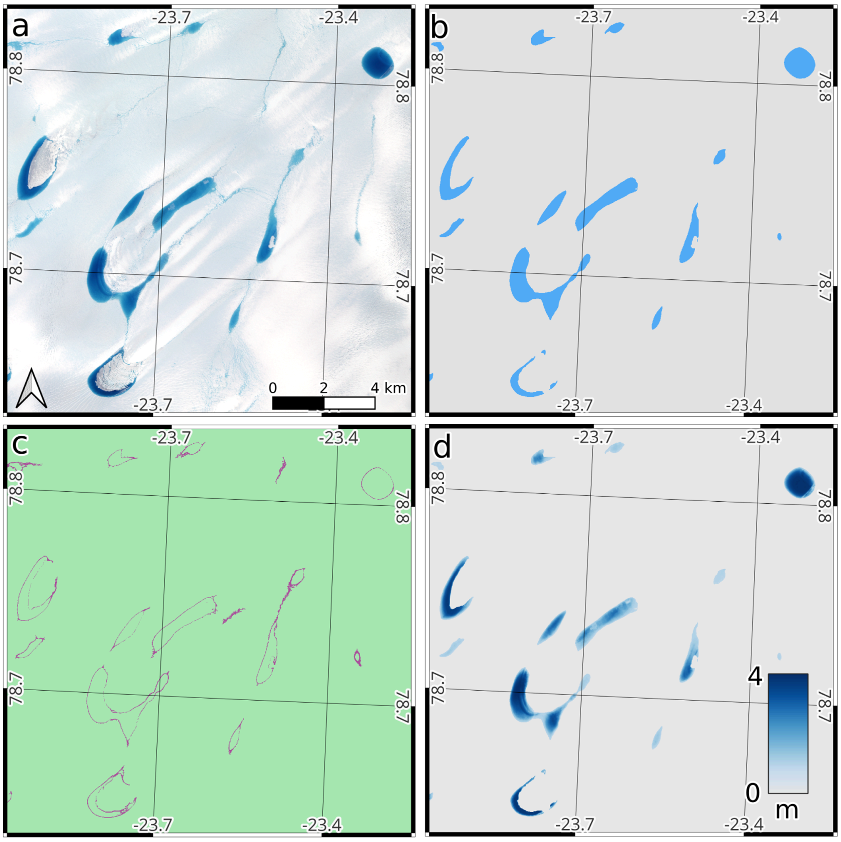
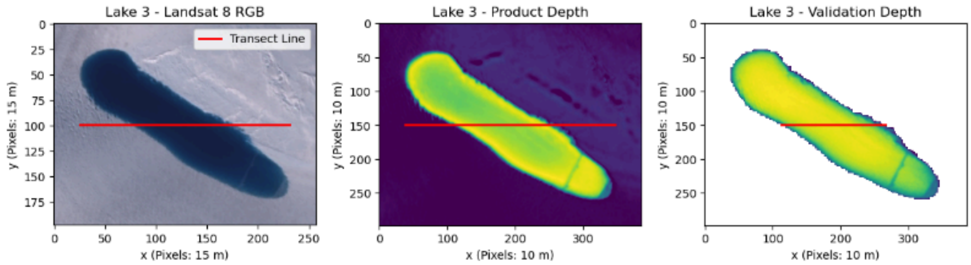


Figure 2.4: From pre-validation samples on 79N; Top left(a): Sentinel-2 RGB sample, top right(b): SGL extent prediction where blue is lake and grey is background, bottom left(c): SGL extent prediction error where green denotes correct prediction and pink is incorrect, bottom right(d): SGL depth prediction.

The continuation of the work and subsequent validation of the findings demonstrated some shortcomings that seem to stem from the sparsity of the available data. In particular, depth estimation seems plagued by this sparsity, which results in a tendency to underestimate depths when compared to reflectance-based algorithms. These findings were documented in the PVIR, and there are clear directions for how to improve a future product in a continuation of the work performed so far.

We found that there is a need for a better-supported model, w.r.t the data. During validation, we found clear artefacts that indicate both the current issues with predicted mid-lake bulging (Figure 2.5). While depths seem to line up well near the edges of a lake, demonstrating similar curves as one would expect using radiative transfer methods, there is a reversal towards the mean when one moves closer to the middle of the lakes. This phenomenon is likely due to a common issue of context-bound regression techniques, where the lack of contrast within the receptive field will result in a trend towards the mean/bias of the regression task.



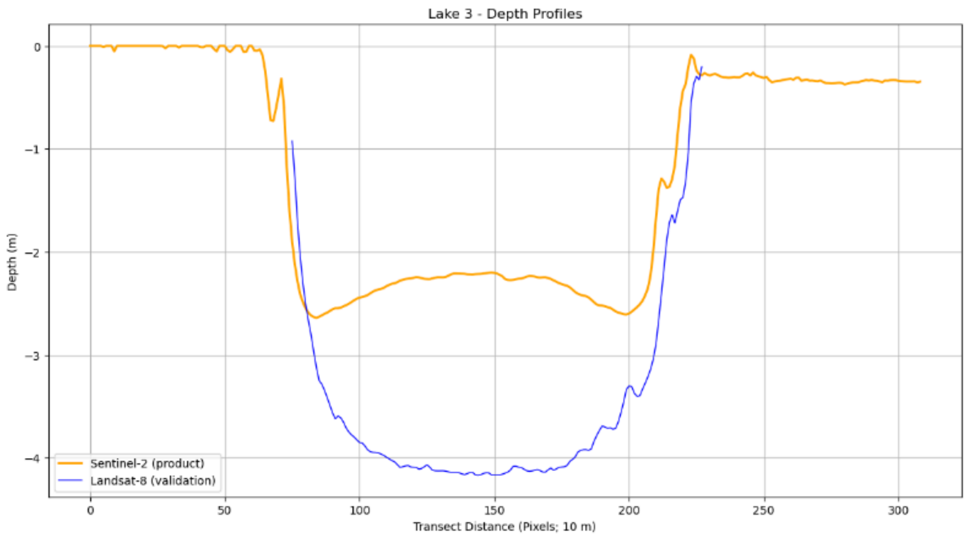


Figure 2.5: Lake depth transection profile from validation, showing the clearest example of the mid-lake bulge predicted for the depth estimates.

Similarly, we found a clear bias in the model prediction of the ice sheet per se, where it will capture the curves of the glacier as having depth. Utility-wise this bias would be cut out when clipping lake depths using the lake extents as a masking feature, but for the scientific validation, we excluded this post-processing step to develop a clearer image of what the model has learned.

Over the SK glacier, there were fewer indications of model generalisation; Here we saw an overall increase in the underestimations of lake depths, showing that there is likely some learned bias towards features of the 79N glacier. This further suggests the need for a larger set of training data is needed to fully cover the data domain of depth.

In summary, there are indications that a model seems feasible, given the following recommendations:

- More depth data is needed to get a GIS-wide well-generalising model.
- Performing cut-mix / cow-mix or similar techniques is essential to generate full cover lake extents
- For unsupervised learning; a larger variation of different lakes would likely be better. (note: in this phase, we had a maximum of 40 transecting lines available)
- A possible way to increase the data available could be to expand to include multiple melt seasons.
- Using radiative transfer-based data for depths could help fill the depth data with less authoritative samples, similar to how the weak-beam signals were used.

3. Data Release

The following newly generated products have been released:

- Surface Elevation Change (SEC) from ERS-1, ERS-2, Envisat, CryoSat-2 and Sentinel-3 data by DTU Space
- Monthly surface elevation changes from CryoSat-2 data (dSEC) by DTU Space
- 2014-present Greenland ice velocity (IV) timeseries from Copernicus Sentinel-1 SAR by ENVEO
- Greenland Icesheet CCI Experimental Ice Uplift/Subsidence from InSAR Line-of-sight velocity by DTU-N
- Ice Velocity from Sentinel-2 data for 9 outlet key glaciers by S&T NO (OptIV)
- Gravimetric mass balance of the Greenland Ice Sheet from the GRACE and GRACE-FO satellite gravimetry mission by TU Dresden
- Greenland mass balance (GMB) product for the Greenland Ice Sheet from GRACE(-FO) satellite gravimetry (CSR RL06) by DTU Space, computed with the mass point inversion method
- 2014-2023 Mass Flux Ice Discharge based on IV and SEC by GEUS.
- Greenland Ice Sheet CCI Experimental SupraGlacial Lakes (SGL) volume estimate from Sentinel-2 and IceSat-2 missions by S&T NO

4. Outreach

The following papers have been published during this phase of the project:

- Valentina R. Barletta, Andrea Bordoni, Shfaqat Abbas Khan. GNET Derived Mass Balance and Glacial Isostatic Adjustment Constraints for Greenland. Geophysical Research Letters. 2024. https://doi.org/10.1029/2023GL106891
- Thomas Slater, Inès N. Otosaka, Andrew Shepherd, Jan Wuite, Thomas Nagler, Lukas Krieger, Dana Floricioiu, Sainan Sun, Ben Davison and Anna E. Hogg. A fine resolution mass budget of the Antarctic Ice Sheet. Geophysical Research Letters. 2024, Under Review.
- Richard Parsons, Sainan Sun, G. Hilmar Gudmundsson, Jan Wuite, and Thomas Nagler. Quantifying the Buttressing Contribution of Sea Ice to Crane Glacier. The Cryosphere. 2024, Accepted. http://dx.doi.org/10.5194/egusphere-2024-1499
- Nitin Ravinder, Inès N. Otosaka, Andrew Shepherd, Thomas Slater, Alan Mur, Lin Gilbert. Greenland Ice Sheet Elevation Change from CryoSat-2 and ICESat-2. Geophysical Research Letters. 2024, Submitted.
- Khosro Ghobadi-Far, Susanna Werth, Manoochehr Shirzaei, Bryant D. Loomis, Thorben Döhne, Matthias O. Willen, Martin Horwath. The Impact of New Accelerometer Transplant Data (ACH) on GRACE Follow-On Along-Orbit Inter-Satellite Laser Ranging Observations and Monthly Time-Variable Gravity and Mascon Solutions. Journal of Geophysical Research: Solid Earth. 2023. https://doi.org/10.1029/2023JB026740
- Otosaka, I. N., Horwath, M., Mottram, R., & Nowicki, S. Mass balances of the Antarctic and Greenland ice sheets monitored from space. Surveys in Geophysics. 2023. https://doi.org/10.1007/s10712-023-09795-8
- Danjal Berg, Valentina Barletta, et al.. Vertical land motion due to present-day ice loss from Greenland's and Canada's peripheral glaciers. AGU Geophysical Research Letters. 2023. https://doi.org/10.1029/2023GL104851
- Valentina R Barletta, Andrea Bordoni, Shfaqat Abbas Khan. GNET-derived Mass Balance and Glacial Isostatic Adjustment Constraints for Greenland. AGU GRL. 2023. https://doi.org/10.1029/2023GL106891
- Otosaka et al.. Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. Earth System Science Data. 2023. http://doi.org/10.5194/essd-2022-261
- Abigail Elizabeth Robinson, David Völgyes, Martijn Vermeer, Daniele Stefano Maria Fantin, Louise Sandberg Sørensen, Mikkel Aaby Kruse, & Sabine Frosch. Deep learning-based supraglacial lake extent and depth detection on the Greenland Ice Sheet by combining ICESat-2 and Sentinel-2 data. Global Space Conference on climate change 2023. 2023. https://doi.org/10.5281/zenodo.7981531
- Jonas Kvist Andersen, Nicholas Mossor Rathmann, Christine S. Hvidberg, Aslak Grinsted, Anders Kusk, John Peter Merryman Boncori, Jeremie Mouginot. Episodic Subglacial Drainage Outbursts Below the Northeast Greenland Ice Stream. Geophysical Research Letters. 2023. https://doi.org/10.1029/2023GL103240
- Karina von Schuckmann, Audrey Minière, Flora Gues, Francisco José Cuesta-Valero et al. Heat stored in the Earth system 1960–2020: where does the energy go?. Earth System Science Data. 2023. https://doi.org/10.5194/essd-15-1675-2023
- Nicolaj Hansen, Louise Sandberg Sorensen, Giorgio Spada, Daniele Melini, Rene Forsberg, Ruth Mottram, and Sebastian B. Simonsen. Revisiting ice sheet Mass balance: insights into changing dynamics in Greenland and Antarctica from ICESat-2. The Cryosphere Discussions. 2023.
- Thorben Döhne, Martin Horwath, Andreas Groh & Eric Buchta. The sensitivity kernel perspective on GRACE mass change estimates. Journal of Geodesy. 2023. https://doi.org/10.1007/s00190-022-01697-8

5. Summary and final conclusions

In conclusion, the CCI+ GIS phase 2 activities have resulted in a new product release, including SEC, IV, GMB, MFID and SGL data products [RD-8] that align or exceed the target as identified at the beginning of the current phase (Table 2.2).

In the current phase of the project, a new approach for product validation was rolled out. In previous phases, each product was validated by the product owner. In the new approach, all the validation was carried out by an independent partner (ASIAQ). This process has the clear advantage that some inconsistencies and errors were identified. The validation activities are described in delta in the PVIR [RD-4].

The Climate Assessment Report CAR [RD-6] provides an overview of datasets, relevant research activities, and recommendations for future projects. One conclusion in the CAR is that the established nature of the GIS CCI+ means that several high-impact research projects can now use the CCI+ GIS products in novel ways to support research goals. Some examples of such newly initiated projects are the Horizon Europe project ICELINK, ESA X-ECV project ARCFRESH and the ESA Digital Twin Ice Sheets project, along with other projects currently still in negotiation. The CAR supports this conclusion with an extensive case study reported in the CAR and carried out in collaboration with the ESA CCI CMUG that uses the latest generation of polar regional climate models together with SEC, IV, MFID and GMB to evaluate the RCMs and assess regions of potential dynamical instability.

In addition, the climate research group notes the contribution to IPCC via IMBIE and other projects funded by both ESA and Horizon Europe that have extensively used CCI+ GIS data. It further notes the potential contribution to the ice sheet (ISMIP7) part of the up and coming CMIP7 that GrIS CCI data can make-. In the CAR we advocate for further research using CCI datasets, particularly in regional climate modelling, ice sheet dynamics, and SMB processes. In particular, the CRG notes that there is confusion over different SMB datasets and proposes a follow-up project that carefully assesses temporal and spatial biases in different model estimates of SMB and applies these to producing an ensemble estimate of ice sheet SMB that goes beyond conventional ensemble means.

The CAR also emphasises public outreach to enhance the visibility and utility of the project's outputs. Challenges such as inconsistent data grids, basin divisions and metadata attributes are identified, and recommendations on standardising data grids and enhancing accessibility for non-specialists are made. More detail can be found in the CAR on specific points as well as a list of publications that have used GrIS CCI data, beyond those produced inside the consortium, assessing the current range of applications and where these may be used in future.

We have also carried out a user workshop in September 2024, as a side event at the European Polar Science Week. Here, we presented the CCI GIS product portfolio for the users, together with several other CCI projects. For this event, we also developed a user questionnaire together with the CCI+ Antarctica project since many of the users of our data sets are the same. The outcome of the questionnaire will be useful for the preparation of future work. This is all described in detail in the User Workshop Report [RD-7]. Some important conclusions from the UWR were:

- The highest priority should be given to observing areas with the greatest mass imbalance, including ice shelves and outlet glaciers.
- The demand for the existing CCI data products continues to be high, in particular for surface elevation change, Ice velocity, and Ice sheet mass balance.
- Several new CCI products would be in high demand, in particular Ice velocity change, Grounding line migration, Ice sheet mass balance partitioned into surface mass balance change and ice dynamics change.

- The demand for CCI products in high temporal resolution is increasing. In particular, products related to surface melting, hydrology and processes near the grounding line would be useful in high resolution, preferably weekly.

6. References

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