ESA Climate Change Initiative

Greenland_Ice_Sheet_cci+ (GIS_cci+)

Science Highlights Phase 2 Year 1 (SH)

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Change Log

Issue	Author	Affected Section	Change	Status
0.6	S&T	All	Draft version	
1.0	All	All	First version	Released to ESA

Acronyms and Abbreviations

Acronyms	Explanation
ATBD	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CFL	Calving Front Location
CONAE	Comisión Nacional de Actividades Espaciales
CS2	CryoSat-2
CSR	Center for Space Research, University of Austin
DEM	Digital Elevation Model
(D)InSAR	(Differential) Interferometric Synthetic Aperture Radar
DL	Deep Learning
DMI	Danish Meteorological Institute
DTU-N	DTU Microwaves and Remote Sensing Group
DTU-S	DTU Geodynamics Group
E3UB	End-to-End ECV Uncertainty Budget
ECV	Essential Climate Variable
ENU	East North Up
ENVEO	ENVironmental Earth Observation IT GmbH
EO	Earth Observation
ESA	European Space Agency
GCOS	Global Climate Observation System
GCP	Ground Control Point

GEUS	Geological Survey of Denmark and Greenland
GFZ	Deutsche GeoForschungsZentrum
GIA	Glacial Isostatic Adjustment
GIS	Greenland Ice Sheet
GLL	Grounding Line Location
GMB	Gravimetry Mass Balance
GRACE(-FO)	The Gravity Recovery and Climate Experiment (Follow On)
IMBIE	Ice Sheet Mass Balance Inter-Comparison Exercise
InSAR	Interferometric Synthetic Aperture Radar
IPP	Interferometric Post-Processing
IV	Ice Velocity
JPL	NASA Jet Propulsion Laboratory
MAI	Multiple Aperture Interferometry
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
NU	Northumbria University
OT	Offset Tracking
PROMICE	Danish Program for Monitoring of the Greenland Ice Sheet
RA	Radar Altimetry
RMS	Root Mean Square
S&T	Science and Technology AS
S2	Sentinel-2

SAR	Synthetic Aperture Radar
SEC	Surface Elevation Change
SLR	Satellite Laser Ranging
SMB	Surface Mass Balance
SOW	Statement of Work
TEC	Total Electron Content
TOA	Top of Atmosphere
TPROP	Technical Proposal
TUDr	Technische Universität Dresden
UL	University of Leeds
URD	User Requirement Document
TOPS	Terrain Observation by Progressive Scans

1 Introduction

1.1 Purpose and Scope

This document represents a description of Science Highlights (SH) for year 1 activities of the Greenland_Ice_Sheet_cci (GIS_cci) project for CCI+ Phase 2, in accordance to contract and SoW [AD1 and AD2]. The central aim is to provide science highlights designed for public consumption, including illustrating images and appropriate links for more details.

1.2 Document Structure

This document is structured into a single chapter describing the following scientific highlight from:

- Surface Elevation Change (SEC)
- Ice Velocity (IV)
- Gravimetric Mass Balance (GMB)
- Mass Flux and Ice Discharge (MFID)
- Supraglacial Lakes (SGL)

1.3 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	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	-
AD2	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

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

2 Scientific Highlights

The Greenland Ice Sheet changes are some of the most visible manifestations of global climate change. In the ESA CCI and CCI+ projects key Earth Observation data are analysed, and long-term and consistent *essential climate variables (ECVs)* are produced and made available to a general audience. In data generation, there has been a focus on scientific and stakeholder users.

The derived CCI ECVs have demonstrated the generations of systematic, quality-checked time series of ECVs of the Greenland ice sheet changes, going back in time to the beginning of the available space missions. The initial set of ECVs included Surface Elevation Changes from radar altimetry (SEC), Ice velocities from synthetic aperture radar satellites (IV), gravimetric mass balance from the GRACE satellite missions (GMB), as well as calving front locations (CFL) of outlet glaciers and grounding line locations (GLL) of the relatively few outlet glaciers in Greenland with floating tongues. The latter two ECV time series were discontinued in the scaled-down CCI+ programme since many other sources of CFL data were available, GLL data are relatively few, and changes in the few floating glacier fronts are not very large. In the current CCI+ phase 2, we have included mapping of supraglacial lake depths. In the CCI+ programme, the higher level Mass flow ice discharge (MFID) ECV was added using the IV and SEC ECVs. Changes in MFID are essentially the summarised effect of changes in IV and SEC ECVs.

This report represents an update of "Science Highlights" (v.1, June 2020), with additions of new year 2 activities of the CCI+ phase 2 Greenland project. The main activities of the current phase of the project have been dedicated to method and algorithm development, and we have not published any new datasets.

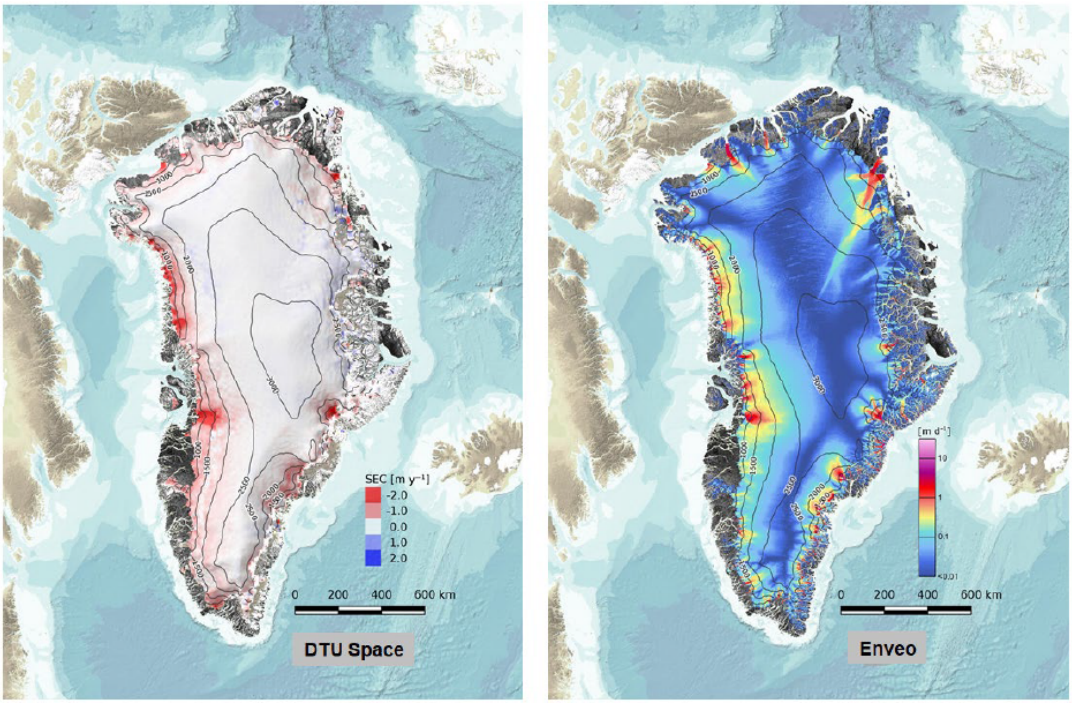

Figure 1: Greenland Ice Sheet changes as measured by elevation changes from CryoSat-2 (left) and ice velocities from Sentinel-1 (right). The largest changes correspond to the major outlet glaciers.

2.1 SEC

The elevation changes of the Greenland ice sheet have been monitored in detail with the radar altimeters on the ESA ERS-1, ERS-2 and EnviSat satellites (1991-2012), satellites with a relatively limited resolution due to the relatively large footprint on the ice sheet, and since 2010 with the ESA CryoSat-2 mission, where new Doppler and interferometric radar technology resulted in a much smaller footprint, and enhanced measurements over the most sloping parts of the ice sheet, where the largest changes take place (Fig. 1). In parallel with this NASAs laser satellites ICESat (2003-9) and ICESat2 (2018-) has provided laser altimetry data over the ice sheet, data which in the present CCI time series are used for validation purposes, because laser altimetry measures (close to) the top of snow. A significant amount of research in the CCI/CCI+ project has been carried out to understand this radar penetration. These studies have also been helped by the inclusion of the higher-frequency radar from the French-Indian AltiKa mission, and the direct surface measurement of ICESat-2 (the ICESat-2 processing is currently ongoing in CCI+).

Completely new algorithms and implementations are being developed in year 1 of the CCI+ phase 2 project and will be used for the next ECV data release, and also “ported” to support the processing of radar altimetry data for the Copernicus Climate Change Service, including data from Sentinel-3. The new implementations allow for higher resolution elevation changes than the previous SEC datasets. We will continue the production of the already existing SEC product. Results of height changes converted to mass changes by firn density and firn compaction models, have been presented in Simonsen et al. (2021) and intercompared with GRACE/GRACE-FO results, as well as input-output methods. The results, shown in Fig. 2, represent a significantly improved and reconciled overall estimate of Greenland ice sheet melt since 1993. The comparison to the older released SEC data, converted to GMB with more crude firn model data (e.g. Forsberg et al. 2017; Shepherd et al., 2019) shows that the fit between GMB from satellite altimetry and GMB from GRACE/GRACE-FO now are much more consistent, earlier misfits could be up to 30-40 GT/yr, especially due to the lack of SEC data closed to the edges of the ice sheet, and the lack of SEC data on smaller outlying ice caps and glaciers.

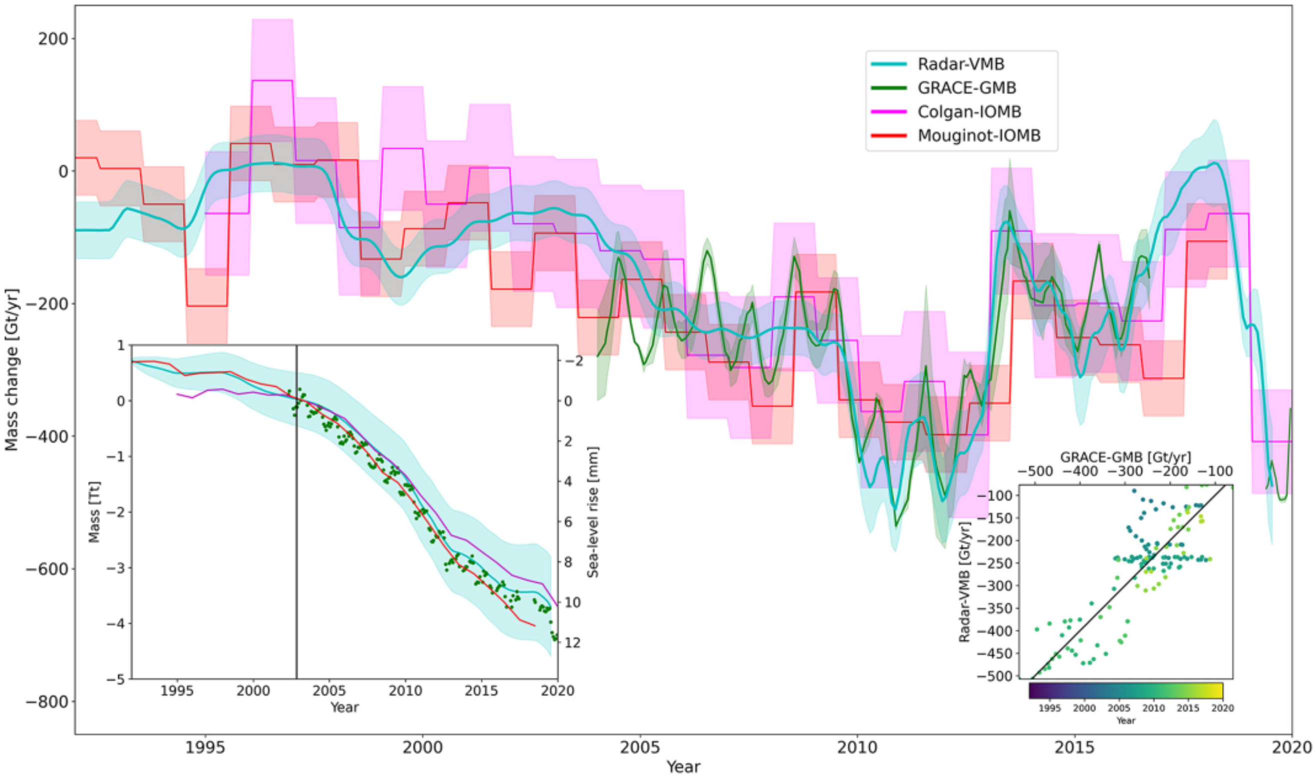

Figure 2: 28-year time series of radar altimetry-derived mass balance for the Greenland ice sheet (cyan). The green curve shows the 2-year temporal-derivative of the GRACE mass balance record, the red curve is the long time series IO-based mass balance estimate from Mouginot et al. 2019, and the magenta is the IO-based mass balance estimate from Colgan et al. 2019. The lower left inset shows the 1992–2020 sea-level rise contribution from the different methods. Lower right inset: correlation of radar-derived MB and GRACE/GRACE-FO MB, as a function of time.

2.2 IV

Ice velocity (IV) is an essential climate variable, providing key input for ice dynamics and climate studies aiming to investigate the ice sheets' response to changing environmental conditions. Combined with detailed radar measurements of ice thickness and modelled SMB, the mass flux (MFID) and overall mass balance may also be determined using the Input-Output Method (IOM).

Analysis of DInSAR time-series of Sentinel-1 data, generated with the algorithm of Andersen et al., 2020, and applied to the interior regions of the Greenland ice sheet, was proven to be an excellent tool for studying the hydrology of the ice sheet, by observing subtle subsidence and uplift patterns related to sub- and supraglacial lake drainage events (Andersen et al., 2023; Maier et al., 2023). This elicits the interest for a time-series IV product, which would enable end-users to more easily carry out this kind of analysis.

In the Greenland Ice Sheet CCI+ IV is derived from both SAR and optical data using combinations of coherent and incoherent offset tracking (OT) and InSAR. The main technical development on SAR-derived IV in CCI+ Phase 1 was the extension of the IV processor for supporting Sentinel-1 TOPS mode InSAR, using ascending and descending crossing orbit pairs acquired in Interferometric Wide (IW) swath mode. The development significantly improved the accuracy of the ice velocity, in particular in the slower-moving areas in the interior of Greenland. Recently, however, the loss of Sentinel-1B has hampered the application of InSAR due to the reduced repeat-pass period from 6 to 12 days as well as the reduced coverage of crossing-orbits pairs.

As a possible way to fill in the gap in SAR coverage and in preparation for the upcoming L-Band missions ROSE-L and NISAR, the main upgrade of the IV processing chain introduced in this phase of the project is the adaptation of the InSAR and OT algorithms to accommodate SAOCOM L-Band SAR data in synergy with Sentinel-1. The SAOCOM mission has acquired 8-day repeat-pass L-Band SAR data over Greenland as a background mission (i.e. without a systematic acquisition plan) since 2021.

By using L-Band SAR data the use of the InSAR method can be extended to cover faster-moving areas than possible with C-band (Sentinel-1). L-band data have a reduced fringe frequency in shear zones and fast-moving areas, enabling more reliable phase unwrapping so that the InSAR method can be applied in zones where Sentinel-1 data decorrelate. Additionally, the L-band signal coherence is less affected by variable surface conditions than C-band. Consequently, further improvement in ice velocity monitoring can be expected from the synergy of C-band and L-band InSAR data, as rendered possible by combining Sentinel-1 and SAOCOM A/B.

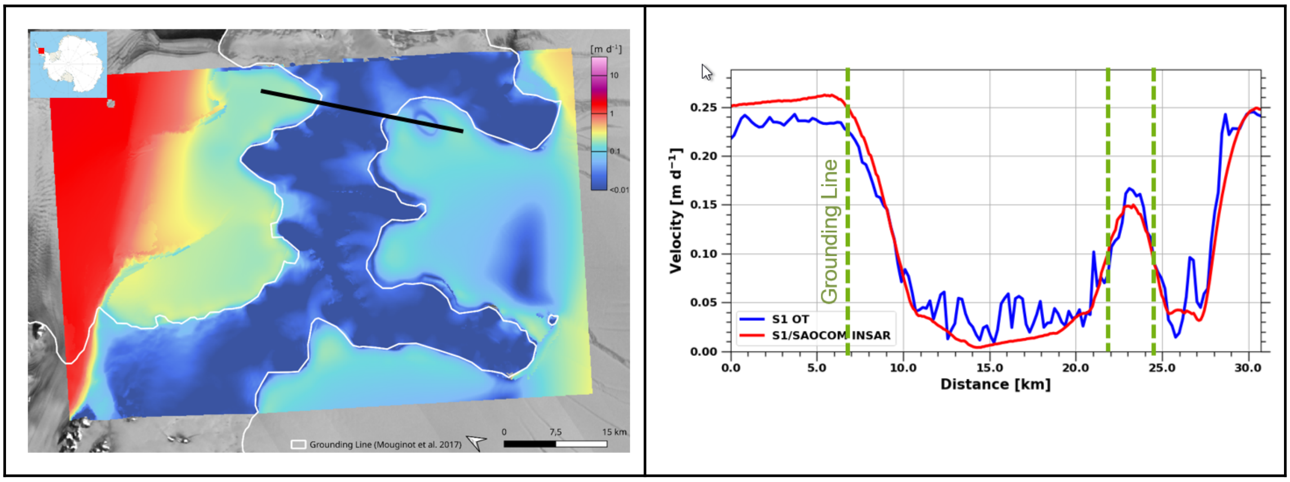

Figure 3: Left: Ice velocity on the Jason Peninsula (Antarctic Peninsula) derived from InSAR using crossing orbits from Sentinel-1 and SAOCOM in combination with OT-derived flow directions. Right: Velocity profiles showing a comparison between ice velocities derived from Sentinel-1 OT (blue) and S1/SAOCOM InSAR (red) along the black line depicted in the left panel.

We tested the SAOCOM data for improving ice surface velocity estimation on ice sheets. First tests, combining SAOCOM and Sentinel-1 derived ice velocity using both InSAR and OT, have been done for Greenland and Antarctica (Fig. 3). The test shows major improvements for IV monitoring using the synergy of C- & L-band InSAR, demonstrated by combining S1 and SAOCOM data. L-/C-band (SAOCOM/S1) InSAR combination provides smooth ice flow over a wide range of velocity magnitudes. The improvement enables monitoring of small tributaries in great detail and provides more accurate discharge estimates, providing better constraints on ice flow models and improving current mass balance estimates.

Additional focus has also been on the development of high-resolution optical ice velocity data from Sentinel-2, complementing SAR interferometry methods, which have various degrees of problems mapping ice velocity during the summer melt period (Fig. 4). A new Norwegian-led CCI+ project extensions (CCN1) have been initiated for enhancing automated mapping of IV, and an additional project looking at the use of AI and Machine Learning for improving this process has just been initiated, building in part on another short-term ESA project on AI for use of Calving Front determination from optical satellite data ("COLD-ML"), with an example also shown in Fig. 4.

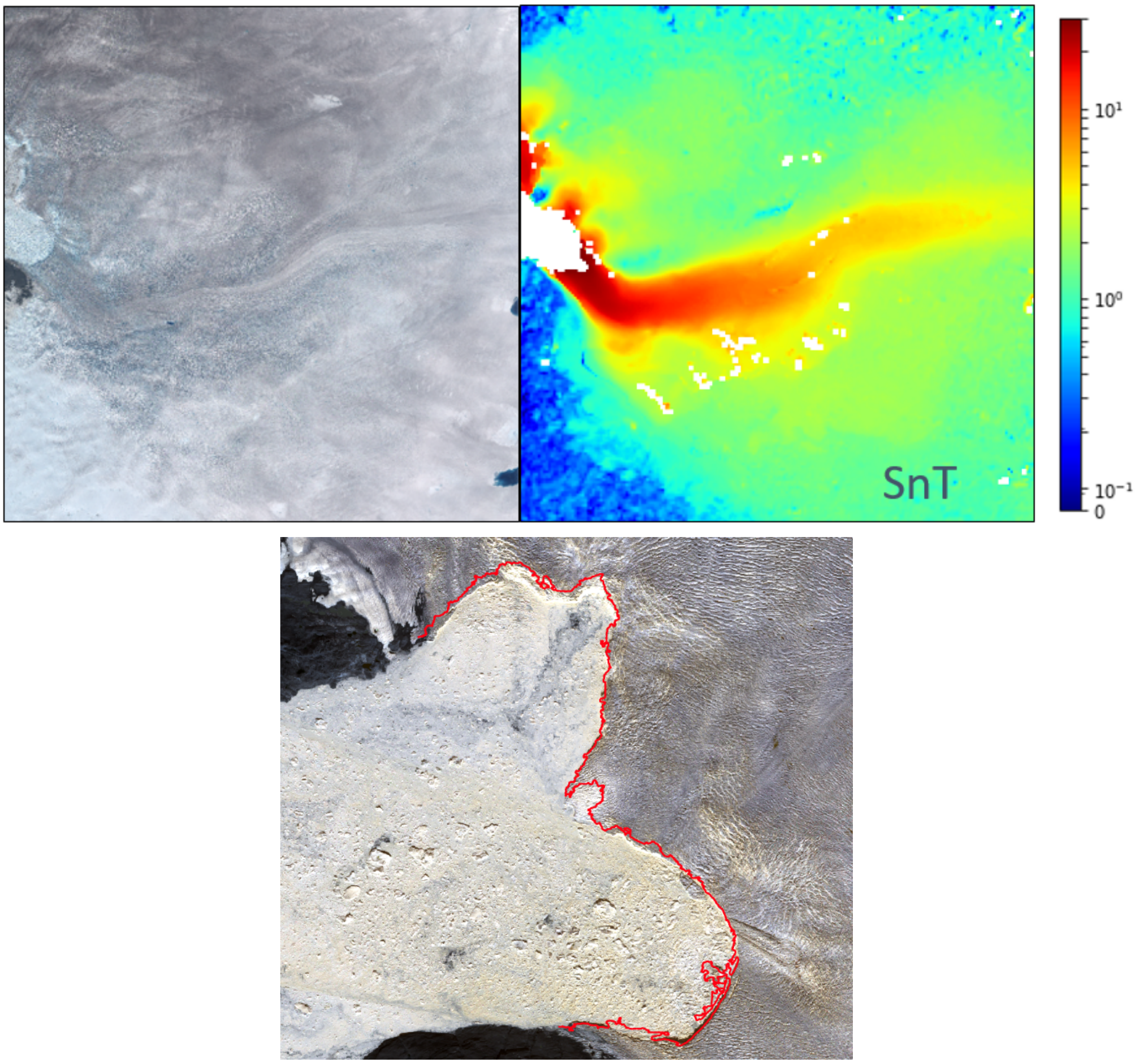

Figure 4: Example of summer optical high-resolution ice velocities, Jakobshavn Glacier. Top left: SAR imagery; top right: 50 m resolution ice velocities (m/day), August 2019 (right); the rapidly moving ice stream is clearly seen on the SAR imagery. Lower: Zoom-in on the calving front, showing the calving front determined by AI (COLD-ML project). The width of the ice fjord between ice-free land on the left is about 10 km.

2.3 GMB

The US/German GRACE mission 2003-2017, and the GRACE-FO mission (2018-), have provided a unique possibility to directly map the overall mass balance of the Greenland ice sheet, although with a limited resolution, a consequence of the satellite gravity field measurements being taken at high altitude (480-420 km). There is also an intrinsic level of uncertainty due to the unavoidable "leakage" when isolating the Greenland mass change signal from other signals (such as ocean changes or melting Canadian ice caps), and the glacial isostatic adjustment (GIA) mass change signals from the shift of masses in the interior of the earth (when the Greenland ice sheet melt, the land under the ice rises, with an associated GIA effect). Because there are different ways of handling the "leakage" and other sources of errors, two different methods were used to generate the mass change signals in the CCI/CCI+ project, with DTU using a mascon estimation approach, and TU Dresden a spherical harmonic filtering approach.

The CCI GMB data produced consists of monthly time series of basin-averaged ice mass changes for different drainage basins of the Greenland Ice Sheet and the entire ice sheet. In addition, maps of the changes on a 50 x 50 km grid are made available (the actual resolution is at best only at the 200-300 km level). DTU Space and TU Dresden have, as part of the product development, done extensive research on the role of the different parts of the solution spectrum (low-harmonics C_{20}, C_3-terms), and the applied glacial isostatic adjustment model correction, as well as the role of the underlying "level-1" processing solutions (CSR or GFZ "raw" data solutions). Recently GRACE and GRACE-FO solutions have been shown to agree well along the one-year mission gap (2017-18), and time series and grids up to 2022 have been released.

For 2003 – 2022, the inferred mass change time series reveals distinct mass losses for all drainage basins under investigation. The time series shows large multi-year changes, in accordance with climatic changes, with 2012 and 2019 being record melt years. The average mass loss for the Greenland ice sheet in the GRACE period 2002-19 is around -255 GT/year, corresponding to a global sea level rise of 0.7 mm/year. The trends on the basin and multi-year scales are quite varying, as also evident in Figure 4, where the overall melt of the GIS showed an anomalous "slow-down" in 2013-18, in connection with relatively colder summer periods.

Work in year one of GIS_cci+ Phase 2 has concentrated on improving the GIA modelling that underlies the GIA correction and improving the methodology of ice mass change inferences from GRACE/GRACE-FO spherical harmonic gravity field solutions. Döhne et al. (2023) elaborate a framework for investigating this methodology.

Intercomparisons of the two independent processing methods have confirmed agreement at better than 5% levels, with complete agreement not possible due to the inherent leakage errors in either method, a.o. related to the separation of Canadian glacier changes (especially Ellesmere Island) from Greenland changes, which is basically a problem related to the limited resolution of the GMB measurements from space.

The two GMB solutions contributed to the continuing efforts of the Ice-Sheet Mass Balance Intercomparison Exercise (IMBIE), the latest update of which was published by Otosaka et al. (2023) (which the DTU and TU Dresden GMB contributions labelled as "Forsberg" and "Groh", respectively).

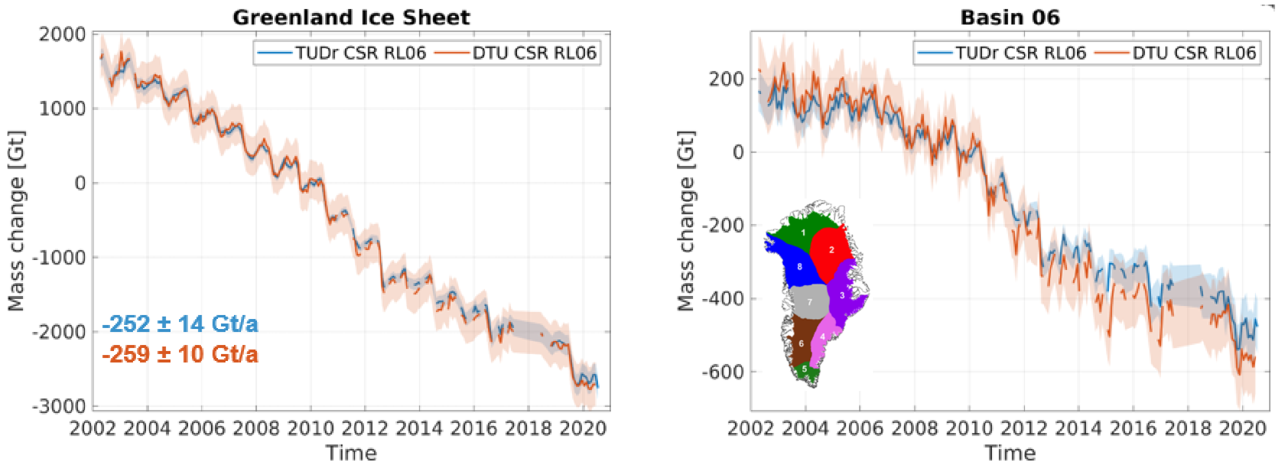

Figure 4. Left: Time series of GRACE-derived ice mass change for the entire Greenland ice sheet for both GMB estimation methods, and associated error estimates; right: Example of Zwally Basin 6 mass change (SW Greenland, see insert). The smooth line segment 2017-19 is due to the GRACE/GRACE-FO gap.

2.4 MFID

The Mass Flow rate and Ice Discharge (MFID) ECV product captures the mass loss of major glaciers flowing from the Greenland ice sheet and entering the surrounding fjords and oceans. The MFID is a key input for calculating and understanding the total mass loss from the ice sheet by the “input-output” method, when combined with surface mass balance data in the interior part of the ice sheet and basal mass loss estimations (see for example Mankoff et al., 2021). Together with GRACE/GRACE-FO GMB, and the mass estimates from SEC, the “input-output” method is the foundation of an independent measure of overall ice sheet mass loss, as demonstrated in the recent ESA/NASA IMBIE Greenland mass change comparison (Otosaka et al, 2023). Contrary to the other measures of overall ice sheet mass loss, the “input-output” method offers the possibility to partition the different mass balance components and understand the processes causing the ice sheet change.

The MFID is calculated as flux changes through gates at all marine-terminating margins of the Greenland ice sheet from a combination of ice thickness and ice velocity. 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 surface elevation from ArcticDEM v3 (cite) and the thickness changes are determined from the SEC ECV. The major contributor to changes in MFID comes from ice flow change which is provided by the IV ECV. Thus, MFID is a higher-level ECV meaning that it combines the observations of IV and SEC into a mass balance term for the “input-output” method. When IV and SEC data are updated so is MFID. The product is published as a sum for each of the Zwally basins.

The gates are automatically defined by an algorithm detecting fast-flowing areas (faster than 150 m/yr) with a distance of 10 km from the ice-ocean boundary. The baseline velocity to determine the fast-flowing ice is the average winter velocity from 2018 to 2020. Each gate consists of a group of pixels of the size 200x200m. The gates are updated in the CCI+ Phase 2 with the latest ice mask as several glaciers have been retreating kilometres since the CCI+ Phase 1.

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. In the CCI+ Phase 2, there is a focus on algorithm development to lower uncertainties in the thickness calculations. Earlier versions of the algorithm calculated MFID based on elevation changes to the gate pixels consisting of an elevation mosaic spanning the period from 2003 to 2009. 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.

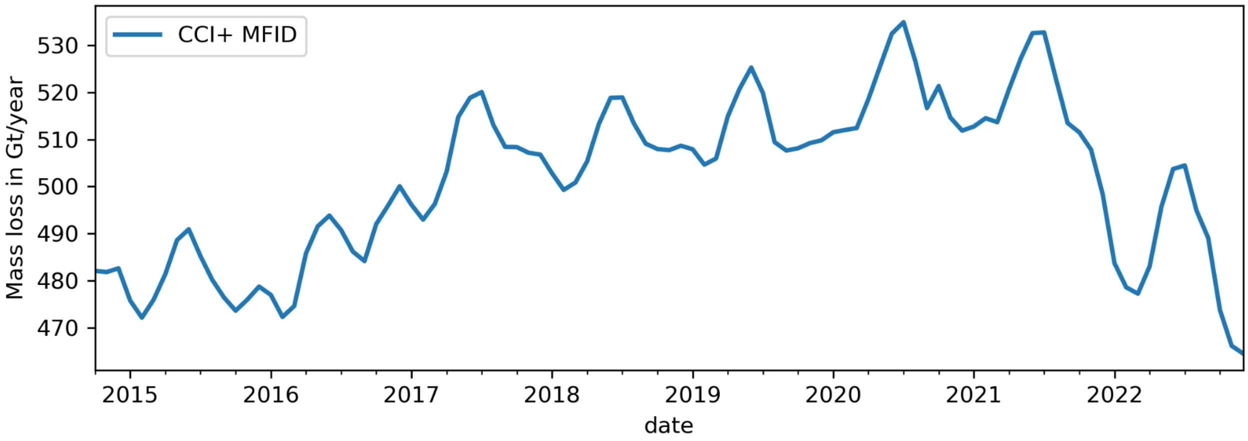

Figure 5: The preliminary results for MFID for CCI+ Phase 2, showing the derived mass loss in Gt due to the flux of ice to the ocean.

The total ice sheet discharge is seen increasing slightly from late 2014 through 2022 (Figure 5). This increase is caused by a general speed-up of the ice. The MFID as a component in the "input-output" method is evaluated by comparing the partitioned components to the Greenland ice sheet mass balance (Mankoff et al., 2021) in Figure 6. As a component in the partitioned total mass balance, the MFID ECV is comparable to equivalent estimates (plotted as D in Figure 6). Furthermore, the comparison in Figure 6 shows that MFID is a key component in the overall trend in total mass balance, but interannual variations are orders of magnitude smaller than the interannual variability in surface mass balance.

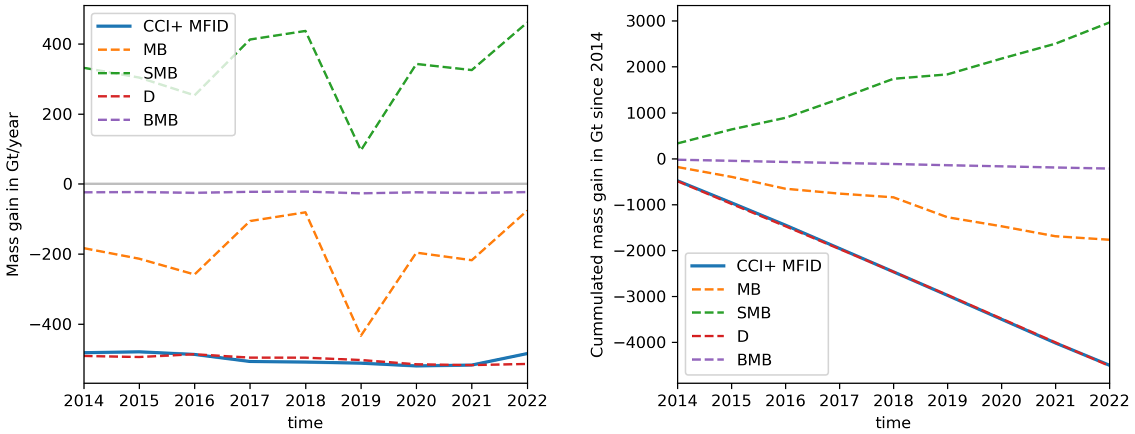

Figure 6: The CCI+ MFID ECV compared to the partitioned total mass balance from Mankoff et al., 2021. MB is total mass balance, SMB is the surface mass balance, D is the solid ice discharge component equivalent to MFID and BMB is basal mass balance.

2.5 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 ICESat2. 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. 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. The preliminary results show that the methodology is feasible as the output model successfully produces a reasonable lake extent and depth prediction despite data limitations.

The Supraglacial Lakes (SGL) experimental product will be generated for two "hot-spot" glaciers, the Nioghalvfjerdsbræ and Zachariæ Isstrøm (hereafter 79°N and Zachariæ, respectively) for the 2019 summer melt season (May to October).

Preliminary results (Figure 7) have been presented at the Global Space Conference on climate change 2023 (GLOC 2023), which was held in Oslo, Norway on 23-25 May, and published in the peer-reviewed conference proceeding. Link to the publication here.

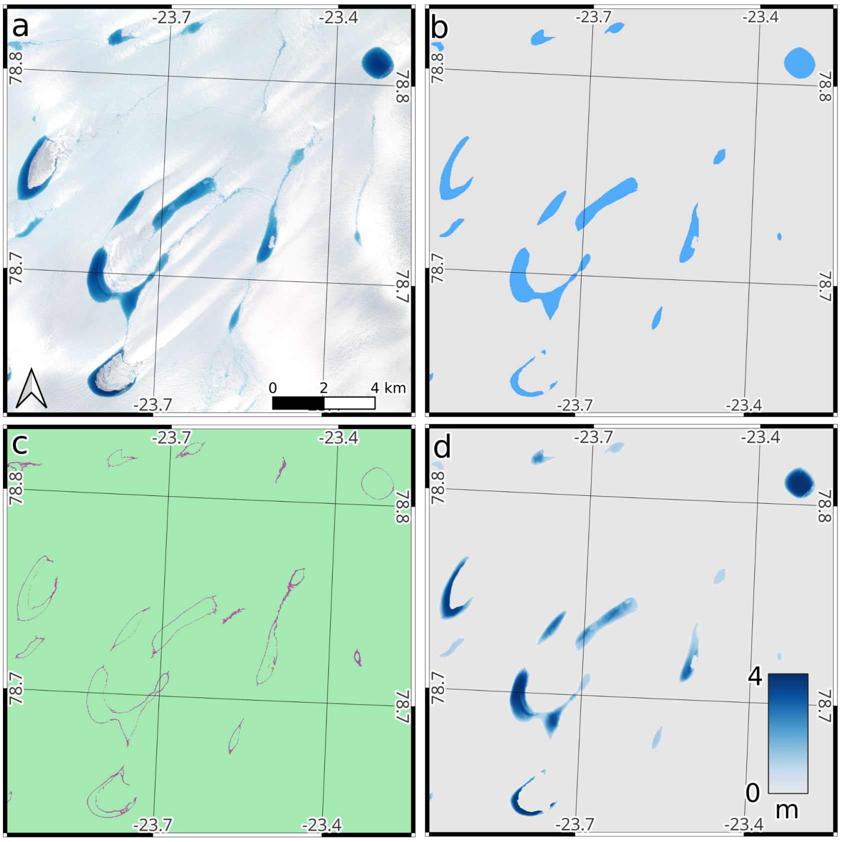

Figure 7: Top left(a): Sentinel-2 RGB sample, top right(b): SGL extent prediction where blue is lake and grey is background, bottom left(c): SGL extent prediction error where green denotes correct prediction and pink is incorrect, bottom right(d): SGL depth prediction.

3 Conclusions and CCI data links

The CCI+ project will generate extended improved ECV data covering all the major sources of space data, especially related to CryoSat-2, Sentinel-1 and -2, GRACE/GRACE-FO and SAOCOM during year 2. The data will potentially provide many opportunities for detailed scientific investigations, as well as monitoring rapid ice sheet changes. Ongoing efforts will see more use on Sentinel-3 and IceSat-2, and close R&D cooperation, a.o. to improve similar ECV products distributed as part of the Copernicus Climate Change Service. The CCI+ website sees an increasing number of downloads, and regular updates on the status of the project and its results are published on the ESA CCI website.

CCI Greenland website on the Climate Office website:

https://climate.esa.int/en/projects/ice-sheets-greenland/

CCI Greenland data portal:

http://products.esa-icesheets-cci.org/

ESA CCI common open data portal:

https://climate.esa.int/en/odp/#/project/greenland-ice-sheet

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