ESA Climate Change Initiative

Greenland_Ice_Sheet_cci+ (GIS_cci+)

Science Highlights year 2 (SH)

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Acronyms and Abbreviations

Acronyms	Explanation
ATBD	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CCI / CCI+	Climate Change Initiative (Plus)
CFL	Calving Front Location
CS2	CryoSat-2
CSR	Center for Space Research, University of Austin
DEM	Digital Elevation Model
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
ENVEO	ENVironmental Earth Observation GmbH
EO	Earth Observation
GCOS	Global Climate Observation System
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
MFID	The contribution of DTU Space and TU Dresden to the second
NBI	Niels Bohr Institute, University of Copenhagen
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
SLR	Satellite Laser Ranging
SMB	Surface Mass Balance
TOPS	Terrain Observing by Progressive Scans
TUDr	Technische Universität Dresden
UL	University of Leeds

1 Introduction

1.1 Purpose and Scope

This document represents an update of the Science Highlights (SH) document for year 2 activities of the Greenland_Ice_Sheet_cci (GIS_cci) project for CCI+ Phase 1, 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 (SL)

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. 4000126023/19/I-NB + App. 1	CCI+ PHASE 1 - NEW R&D ON CCI ECVS, for Greenland_Ice Sheet_cci	2019.04.01	
AD2	ESA-CCI-EOPS-PRGM-SOW-18-0118 - Appendix 2 to contract.	Climate Change Initiative Extension (CCI+) Phase 1, New R&D on CCI ECVs - SOW	2018.05.31	Issue 1 Revision 6

2 Scientific Highlights

The Greenland Ice Sheet changes are one of the most visible manifestations of global climate change. In the ESA CCI and CCI+ projects (2012-2018 and 2019-2022) key EO satellite data are analysed and made available to a general audience, with focus on scientific and stakeholder users.

The derived CCI time series has demonstrated the generations of systematic, quality-checked time series of key essential variables of the Greenland ice sheet changes, going back in time to the beginning of the available space missions. The initial set of ECV's included Surface Elevation Changes from radar altimetry (SEC), Ice velocities from synthetic aperture radar satellites (IV), gravimetric mass balance from the GRACE satellite mission (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, and GLL data are relatively few, and changes in the few floating glacier fronts not very large.

This report represents an update of "Science Highlights" (v.1, June 2020), with additions of new year 2 activities of the CCI+ Greenland project. The main activities of CCI+ year 2 have focussed on the release of new ECV data sets, as well as major R&D efforts relating to the improvement of the ECV time series.

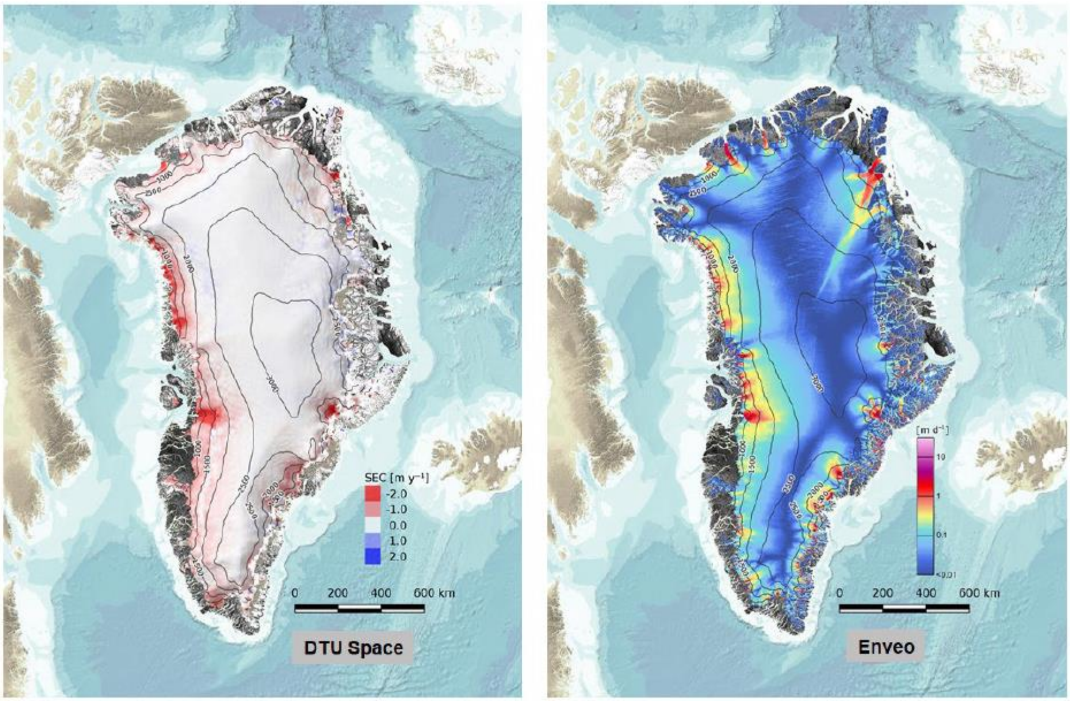

Figure 1: Greenland Ice Sheet changes as measured by elevation changes from CryoSat-2 (left) and ice velocities from Sentinel-1 (right). The largest changes correspond to the major outlet glaciers.

2.1 SEC

The elevation changes of the Greenland ice sheet has been monitored in details 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 NASA 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 have only been used for validation purposes, in part due to the episodic nature of IceSat-1 data collection (2-3 months/year), and the realization that the radar and laser altimetry reflections are not from the same surfaces (radar altimetry measurements tend to reflect first ice horizons or compacted snow layers, while laser altimetry measures the top of snow, and is strongly affected by snowfall events); a significant amount of research in the CCI project have been carried to understand these "radar penetration" effects. These studies have also been helped by inclusion of the higher-frequency radar from the French-Indian AltiKa mission, and the direct surface measurement of with IceSat-2 (the IceSat-2 processing is currently ongoing in CCI+).

Completely new algorithms and implementations have been developed in year 2 of the CCI+ project, and will be used for the fall 2021 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 "seamless" use of various satellite altimeter data, whether in repeat orbit (like Envisat or Sentinel-2), or in drifting orbit (like CryoSat-2). Results of with the new processing scheme, with height changes converted to mass changes by firm 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.

Significant challenges in the SEC time series have been the "melt events" of the Greenland ice sheet, especially in 2012 and 2019, where record hot summers gave large melt and even rainfall across large parts of the Greenland ice sheet, generating re-frozen ice lenses in the firn, which complicated the analysis of radar reflections by CryoSat-2. Other EO data, meteorological models, and airborne data from NASA IceBridge and ESA CryoVEx campaign helped in understanding these effects, and improved the "retracking" algorithms of the radar return waveforms, this improving the SEC products. Together with models of firn compaction and snow densities, such models also are useful for converting elevation changes to mass changes, thus providing independent cross-validation and higher resolution mass balance data, validating indirectly GMB from GRACE.

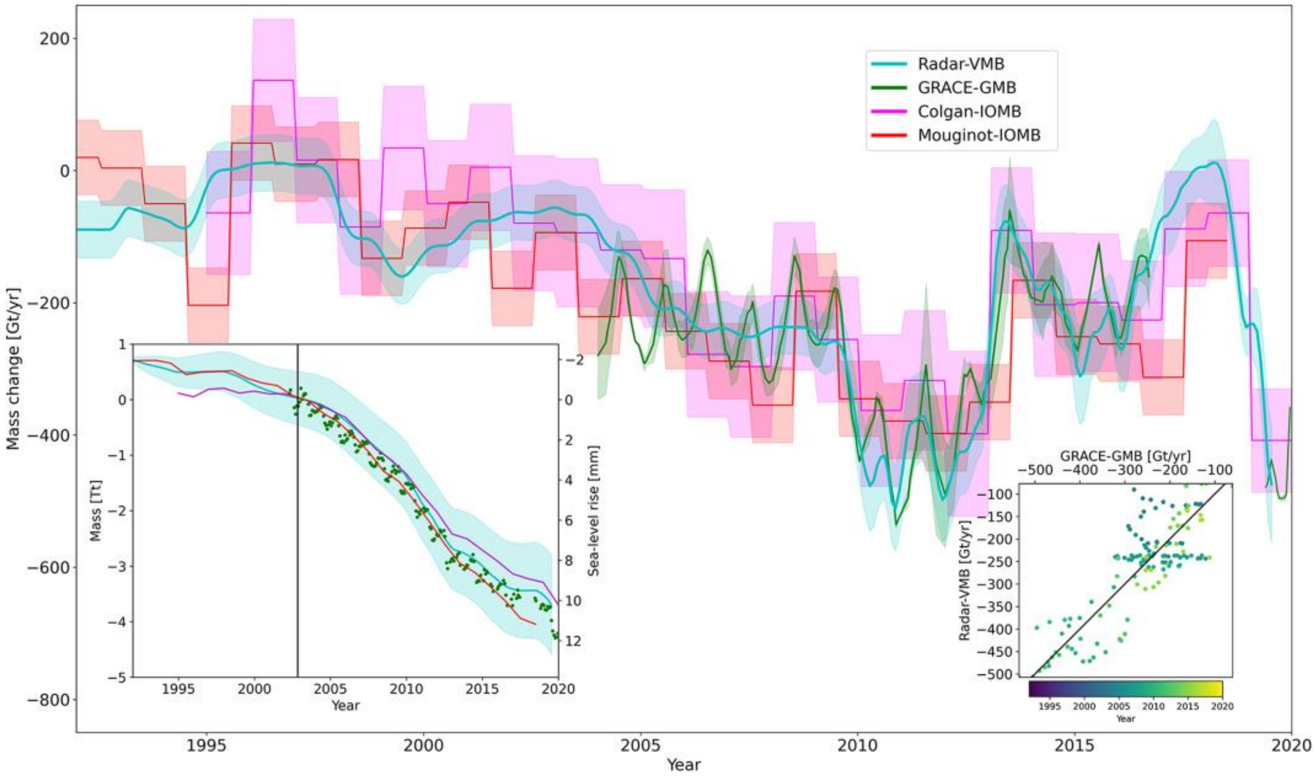

Figure 2: 28-year time-series of radar altimetry-derived mass balance for the Greenland ice sheet (cyan). The green curve shows the 2-year temporal-derivative of the GRACE mass balance record, the red curve is the long time series IO-based mass balance estimate from Mouginot et al. 2019, and the magenta is the IO-based mass balance estimate from Colgan et al. 2019. Lower left inset shows the 1992–2020 sea-level rise contribution from the different method. 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 for quantifying ice sheet discharge, and provides key input for ice dynamic and climate models aiming to investigate the ice sheets response to changing environmental conditions. Combined with detailed radar measurements of ice thickness, the mass flux (MFID) may be determined, and further combined with modelled snow fall in the interior, overall mass balance may also be determined, as illustrated in Fig. 2.

One of the major advancements emerging from the CCI project is the development and implementation of an automatic system for generation of high resolution ice velocity maps from repeat pass Copernicus Sentinel-1 synthetic aperture radar (SAR) data. Taking full advantage of the systematic acquisition planning of Sentinel-1 in Greenland, with continuous 6- to 12-day repeat passes covering the margins and annual ice sheet wide campaigns, we have built a dense archive of Sentinel-1 derived ice velocity maps now spanning more than 5 years, and providing essential information for studying seasonal fluctuations, rapid melt events, and long-term trends.

For IV the further technical developments and production in GIS CCI+ build on these previous achievements, and include an extension of the IV processor for supporting interferometric SAR (InSAR). InSAR can reach a precision of one to two orders of magnitude higher than standard offset tracking techniques and is particularly suitable for improving the precision in the slow moving interior of the ice sheet. However, it requires the combination of both ascending and descending passes, and repeat passes need to be short enough to maintain coherence between image pairs. Preliminary results demonstrate the excellent capability of Sentinel-1 for InSAR applications, unexpectedly also capturing the fast ice flow on a number of outlet glaciers in great detail.

The improvement enables to provide better constraints on ice flow models and improves current mass balance estimates, especially through the mass flux ECV, where mass flux along the margins combined with precipitation in the interior of the ice sheet provide an independent estimate of mass loss through the "input-output" method.

Focus in year 2 of CCI+, in addition to the routine generation of S-1 ice velocity grids (500 m resolution) has been to generate extremely high 50 m resolution products, by a combination of InSAR and feature tracking. These massive data sets are available at the CCI+ partner sites http:\\cryoportal.enveo.at and through DTU Space (Fig. 3).

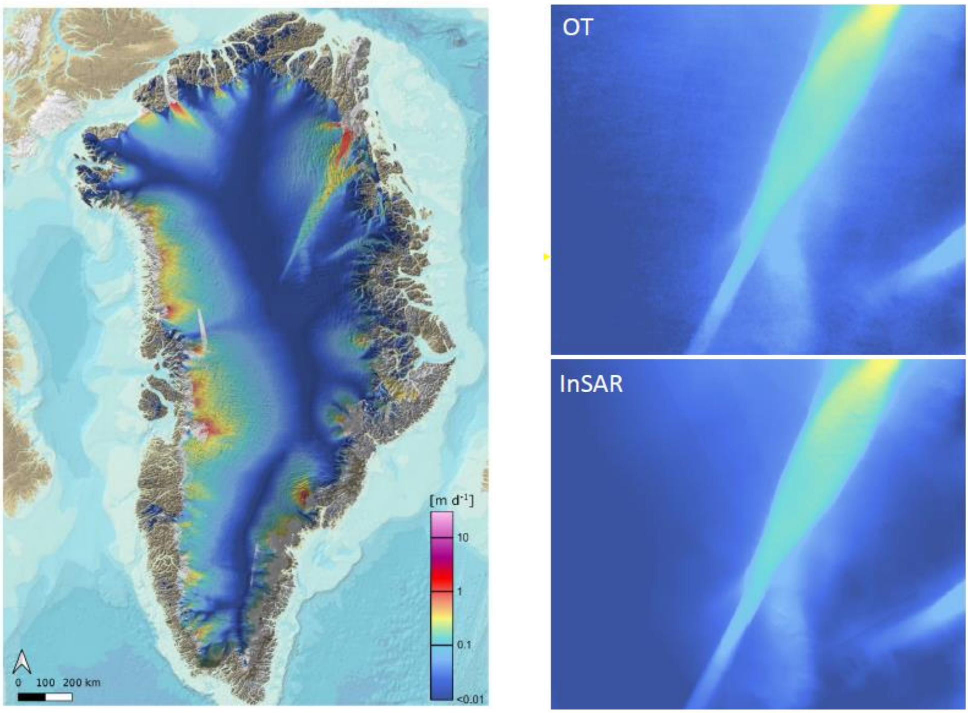

Figure 3: Left: Ultra-high resolution 50 m InSAR ice velocity map from Sentinel-1, acquired during 2018/19 and 2019/20 winter mapping campaigns (ENVEO). Right: Details at the onset of the NE Greenland ice strean for offset tracking (OT) and InSAR processing.

Additional focus has also been on 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 use of AI and Machine Learning for improving this process have 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.

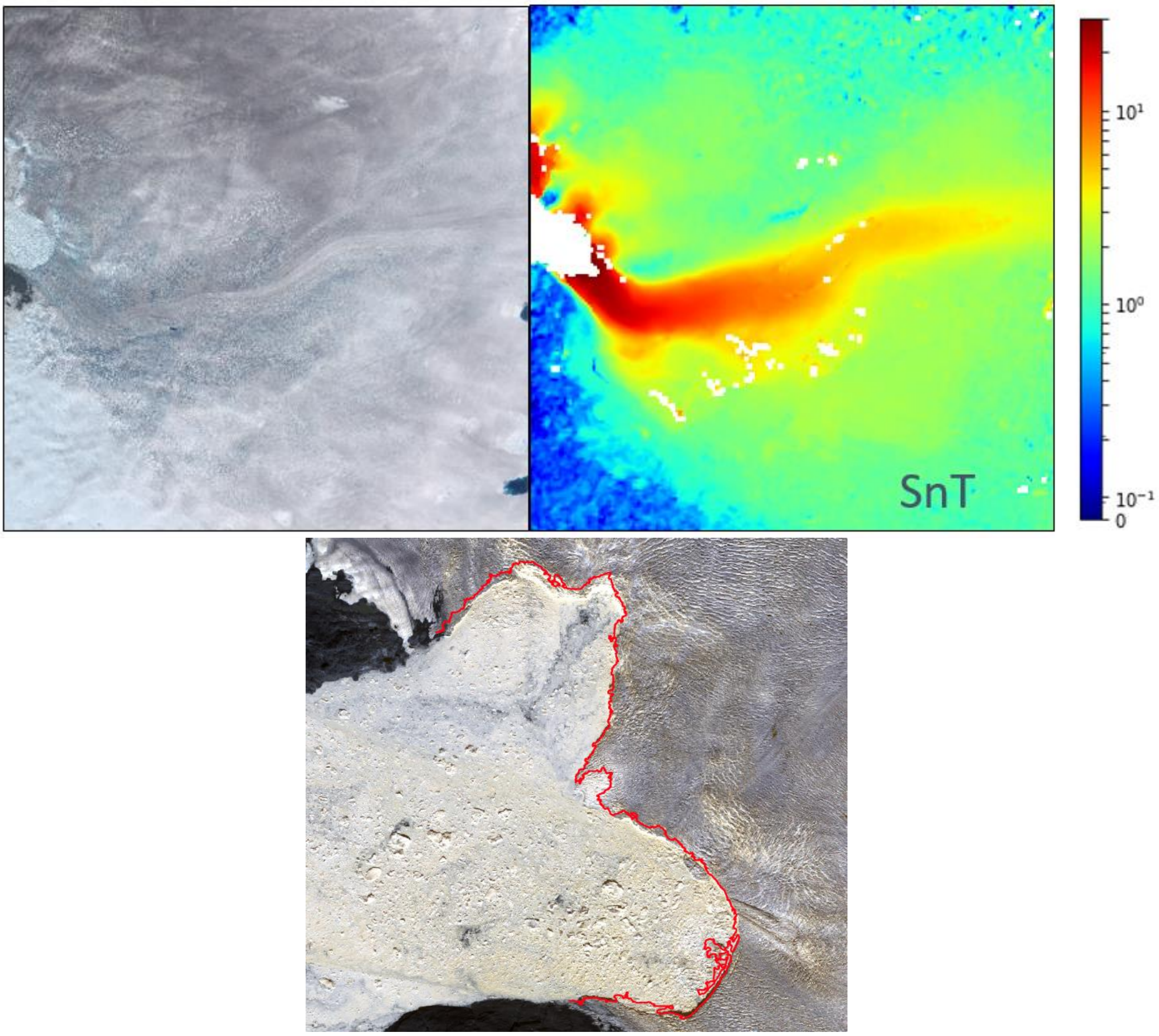

Figure 4: Example of summer optical high-resolution ice velocities, Jakobshavn Glacier. Top left: SAR imagery; top right: 50 m resolution ice velocities (m/day), August 2019 (right); the rapidly moving ice stream is clearly seen on the SAR imagery. Lower: Zoom-in on the calving front, showing calving front determined by AI (COLD-ML project). Width of the ice fjord between ice free land on the left 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 are done at high altitude (480-420 km), 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 of especially the way to handle the "leakage", 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 also maps are made available of the changes on a 50 x 50 km grid (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 2020 have been released.

For the period 2003 – 2020, the inferred mass change time series reveal 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 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.

For the CCI+ second year focus on the GMB estimation have been to improve the algorithm accuracy (slightly) through implementation of ellipsoidal corrections, and otherwise to continue the monthly time series by GRACE-FO. Intercomparisons of the two independent processing methods have confirmed agreement at better than 5% levels, with complete agreement not possible due to the inherent aliasing 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.

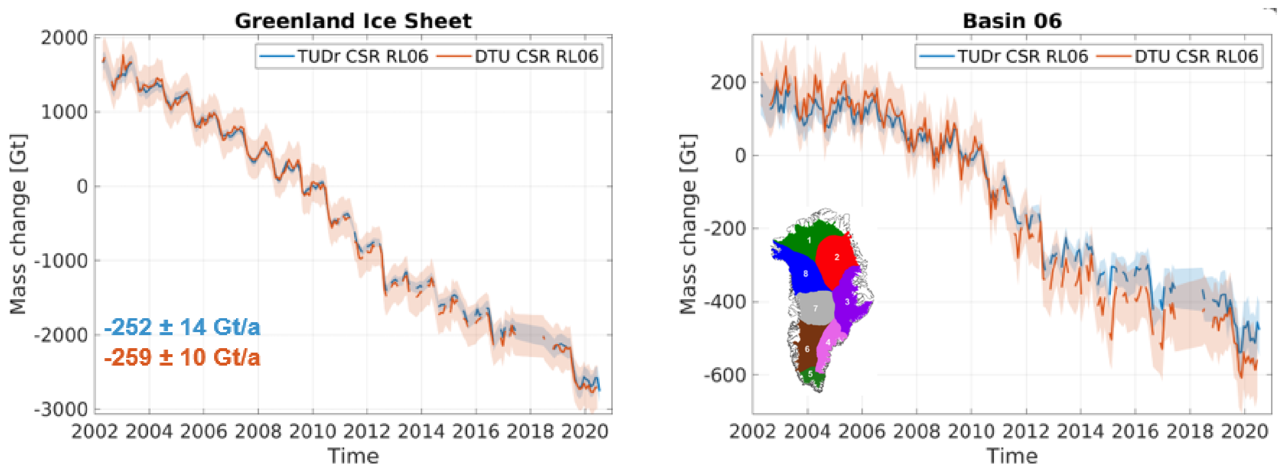

Figure 4. Left: Time series of GRACE-derived ice mass change for the entire Greenland ice sheet for both GMB estimation methods, and associated error estimates; right: Example of Zwally Basin 6 mass change (SW Greenland, see insert). The smooth line segment 2017-19 is due to the GRACE/GRACE-FO gap.

2.4 MFID

The new Mass Flow rate and Ice Discharge (MFID) ECV product in CCI+ captures the mass loss of major glaciers flowing from the Greenland ice sheet and entering the surrounding fjords and oceans. The mass flow rate is a key input for calculating and understanding the total mass loss from the ice sheet by the "input-output" method, when combined with accumulation data in the interior part of the ice sheet. Together with GRACE/GRACE-FO GMB, and the mass estimates from SEC, the MFID is therefore give the foundation of an independent measure of overall ice sheet mass loss, as demonstrated in the recent ESA/NASA IMBIE Greenland mass change comparison (Shepherd et al, 2019), and also shown in Fig. 2.

The MFID is calculated from a combination of ice thickness and ice velocity, with assumptions on no change of ice velocity with ice depth. Ice thickness is determined from airborne radar measurements, mainly from recent campaigns (NASA IceBridge and PROMICE, but also many older data. Some gaps in the thickness data still exist, especially in SE Greenland. Changes in thickness over time are accounted for using updated maps of surface elevation. The Greenland ice-velocity maps are derived from satellite observations, using the CCI velocity product in the released data on the CCI products page (data are here averaged over the same eight "Zwally" drainage basins as used for the GMB time series).

For the underlying detailed investigations, we calculate ice flow rate across flux gates approximately 10 km upstream of marine terminating glaciers. The discharge gates are located using an automated procedure based on the surface ice velocity. The ice, ~10 km downstream from the flux gates, leaves the ice sheet as either icebergs or submarine melting in the fjords.

Large uncertainties exist in the amount of ice leaving the ice sheet because large uncertainties exist in the thickness of the ice. However, changes in time are less uncertain, because most of the change is due only to the surface velocity.

The total ice sheet discharge is seen increasing slightly from late 2014 through mid-2020, in accordance with the general trends in SEC and GMB. Seasonal summer increases and winter decreases are due to ice velocity changing as summer surface melt enters the subglacial system.

The focus in year 2 has been on continuing the MFID monthly time series, averaged across the Zwally basins, and intercomparing estimates from partners GEUS (providing the CCI+ data, and also publishing more detailed data on the PROMICE national monitoring program, www.promice.dk) and ENVEO (publishing MFID on the cryoportal.enveo.at, see Fig. 5). The two estimates differ a.o. on the location of the mass flux "gates", which ideally should be as close to the glacier calving fronts as possible (Fig. 6).

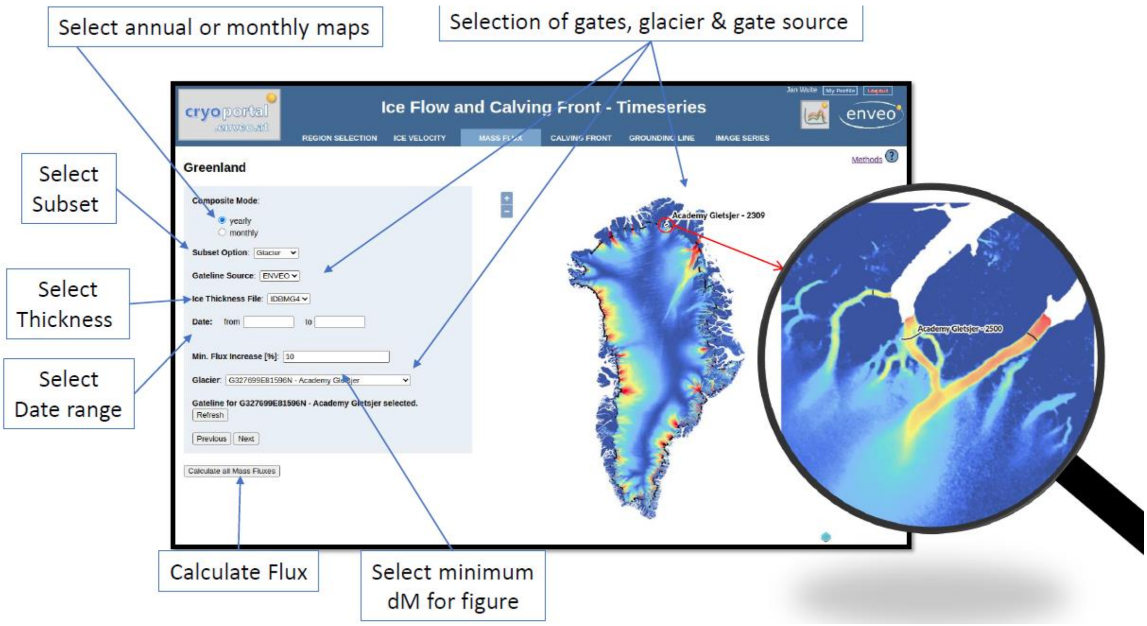

Figure 5. Online MFID tool at cryoportal.enveo.at, allowing detailed MFID data extraction. Zoom-in example are on the Academy and Hagen glaciers, north Greenland.

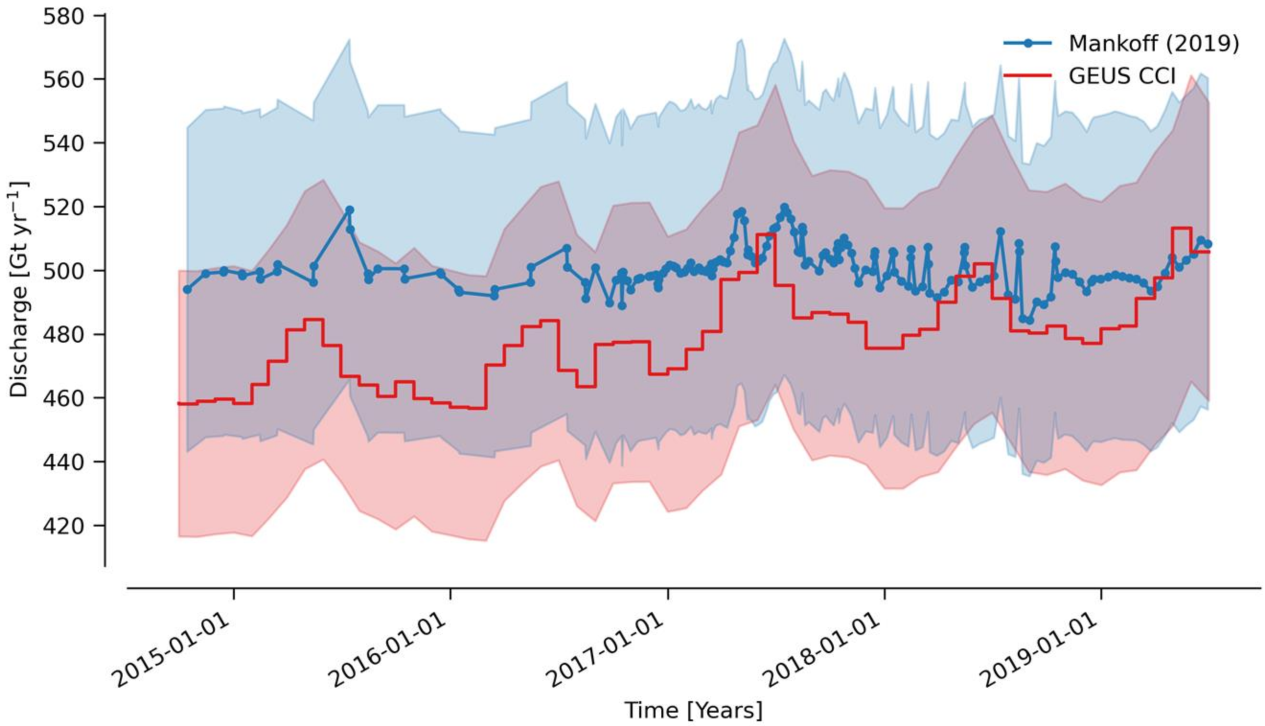

Figure 6. Estimated total ice discharge for the Greenland (outlying icecaps excluded). The CCI data, based on improved CCI S-1 ice velocities are shown in red as monthly estimates; blue data are earlier published data based on NASA/MEASURES data (Mankoff et al, 2020). Data agrees well within error bounds, also shown; the apparent trend difference are mainly due to different selection of outlet glacier "gates".

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 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.

The Supraglacial Lakes (SGL) experimental product is aimed at quantifying the practical monitoring of the growth and drainage of such lakes, and the link to the observed speed-up of outlet glaciers during the summer, and will be generated for two "hot-spot" regions, the Jakobshavn Glacier (Sermeq Kujalleq) drainage basin, as well as the NE Greenland ice stream region.

Supraglacial lakes are water bodies that accumulate in depressions on the surface of the glacier or ice sheet, forming bright blue lakes. Supraglacial lakes begin to develop at the onset of the melt season at lower elevations on the glacier, and extend up glacier as the air temperatures and surface melt increase. Generally, lakes are largest at higher elevations, in some cases greater than 10 km^2.

Supraglacial lakes play a significant role in glacier and ice sheet hydrology and dynamics, both at the surface of the glacier and at the base of the glacier. As they form at the surface, they pool much of the summer melt water that flows into them via a vast network of meltwater streams and rivers. In many cases, these lakes drain rapidly through the ice column and the water enters and overwhelms the subglacial drainage system. This increase in meltwater can act as a form of lubrication at the bed of the glacier, causing it to flow faster. As the glaciers flow faster, they are able to transport more ice from the land into the oceans, which in turn leads to increases in sea level.

For the CCI project, partner ASIAQ detect and map supraglacial lakes using Sentinel-2 satellite data. A band ratio algorithm called the Normalised Difference Water Index (NDWI) is used to the Green and Near Infrared (NIR) bands available from the sensor. This index makes it easy to detect water bodies at the surface of the glaciers and ice sheets. An example of the NDWI is shown in Figure 7, where the water bodies appear bright and the surrounding snow and ice appear dark. Activities are ongoing also to measure depth of selected lakes by IceSat-2.

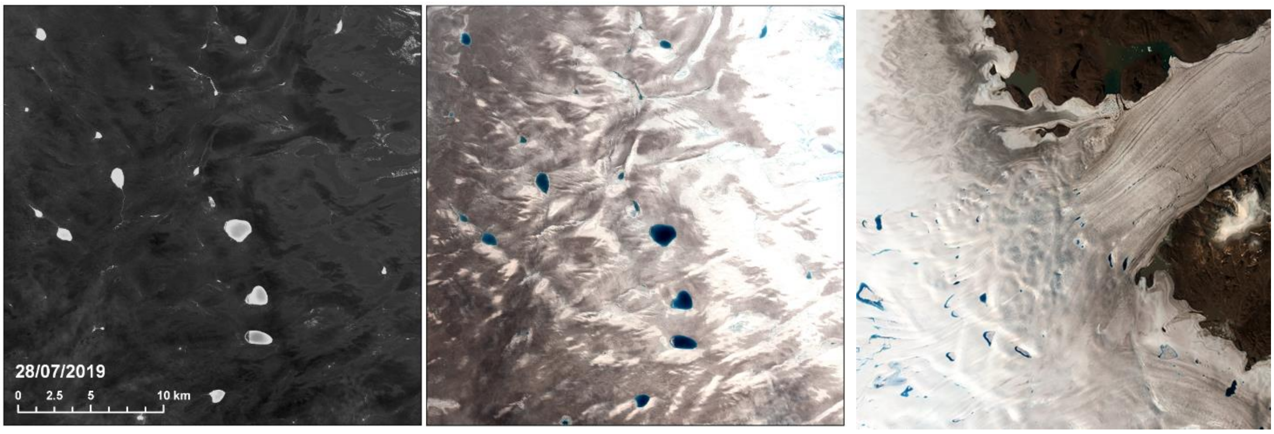

Figure 7. Left: Example of how water appears in a NDWI index. The ice and snow is dark and the supraglacial lakes appear bright. Right: The corresponding RGB image from Sentinel-2. Although the supraglacial lakes are somewhat identifiable in the RGB image, it is often difficult to see water bodies on the dark ice. Data shown here is a Sentinel-2 tile from the Sermeq Kujalleq (Jakobshavn Glacier) catchment.

Once all the supraglacial lakes are detected at the surface, they can automatically be delineated and monitored throughout the melt season and over many years. The supraglacial lakes allow us to examine the changes in the ice sheet ablation zone (where the melting takes place) and how these change through time.

Figure 8 shows the analysis of the summer 2019 lake area and corresponding ice velocities in the Jakobshavn Glacier region. The correlation of velocity changes and lake drainage is not very clear, so more data are needed for more detailed analysis ahead of scientific publication; problems with IV SAR coverage in the summer also complicates the intercomparison, highlighting the need for more optical IV data as well.

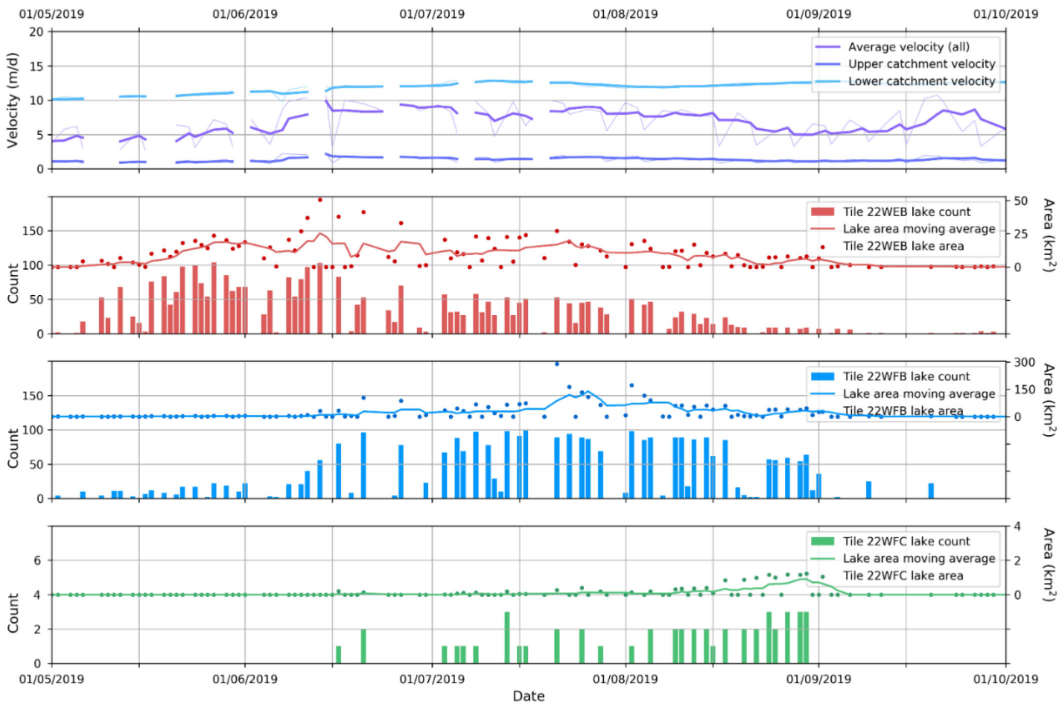

Figure 8. Subglacial lakes data from the Sermeq Kujalleq (Jakobshavn Isbræ) catchment area. Top panel shows the CCI ice velocity from S-1; lower panels show the number of subglacial lakes mapped, with number of lakes (left scale) and total lake area (right scale), for the three analysed Sentinel-3 tiles (WEB,WFB,WFC).

2.6 Conclusions and CCI data links

The CCI+ project continued in year 2 to generate extended improved ECV data covering all the major sources of space data, especially related to CryoSat-2, Sentinel-1 and -2, and GRACE/GRACE-FO. The data will potentially provide many opportunities for detailed scientific investigations, as well monitoring rapid ice sheet changes (Fig. 8). 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. Th e CCI+ web site sees an increasing number of downloads, and content is currently being transferred to the new joint ESA CCI website (with the existing web site being continued for continuity reasons at least until 2022).

CCI Greenland web site:

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

CCI Greenland data portal:

http://esa-icesheets-greenland-cci.org/index.php?q=products

ESA CCI common data portal for Greenland ice sheet:

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

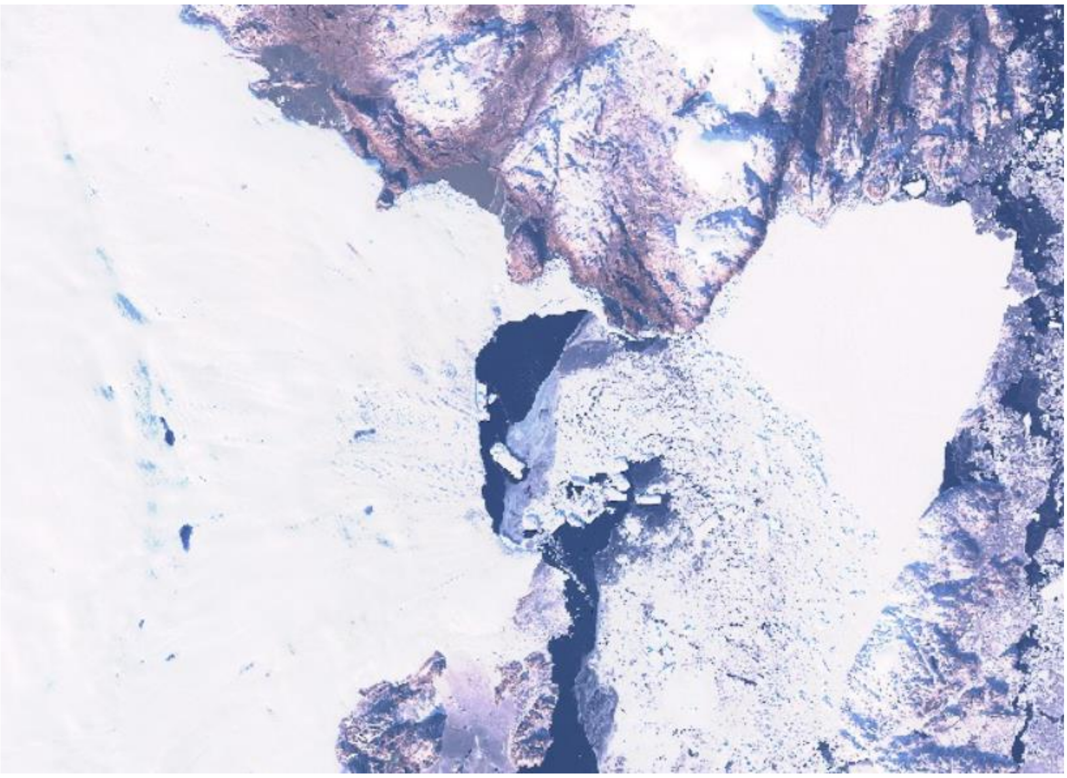

Figure 9. Calving event on the Zachariae Glacier, NE Greenland, August 27, 2020 (Sentinel-1).

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