ESA Climate Change Initiative

Greenland_Ice_Sheet_cci+ (GIS_cci+)

Science Highlights Phase 2 Year 2 (SH)

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Technische Universität Dresden (TUDr)

The Geological Survey of Denmark and Greenland (GEUS)

The Niels Bohr Institute (NBI)

Northumbria University (NU)

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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
2.0	All	All	Second 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

1.4 Purpose and Scope

This document represents a description of Science Highlights (SH) for year 2 activities of the Greenland_Ice_Sheet_cci (GIS_cci) project for CCI+ Phase 2, in accordance with the 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.

1.5 Document Structure

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

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

1.6 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 variable (ECV)* products 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 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. In the current CCI+ phase 2, we have included mapping of supraglacial lake (SGL) 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 some selected "Science Highlights" of our activities in year 2 of phase 2. The main activities of the current phase of the project have been dedicated to product generation, publication and validation.

New algorithms and implementations were developed in year 1 of the CCI+ phase 2 project and these have been used for the current ECV data release

2.1 New surface elevation change data product

The newly developed dSEC algorithm employs advanced statistical modelling and provides high-resolution, monthly maps of surface elevation changes across the Greenland Ice Sheet (GrIS) using CryoSat-2 data.

The dSEC approach leverages a state-space model (SSM) that ensures robust results even in data-sparse regions. By incorporating both spatial and temporal dependencies, the algorithm reconstructs robust elevation change. Spatial gaps in satellite tracks are addressed using a Gaussian Markov Random Field, while temporal trends are modelled with an autoregressive process.

Figure 1 showcases the elevation change across the GrIS in one month, together with the time series for five glaciers and one point in the centre for the entire CryoSat-2 measurement period.

The visualization of elevation change highlights areas of significant thinning and thickening, revealing seasonal and interannual ice dynamics, and providing insights into ice dynamics and Greenland's response to climate change and variability due to weather.

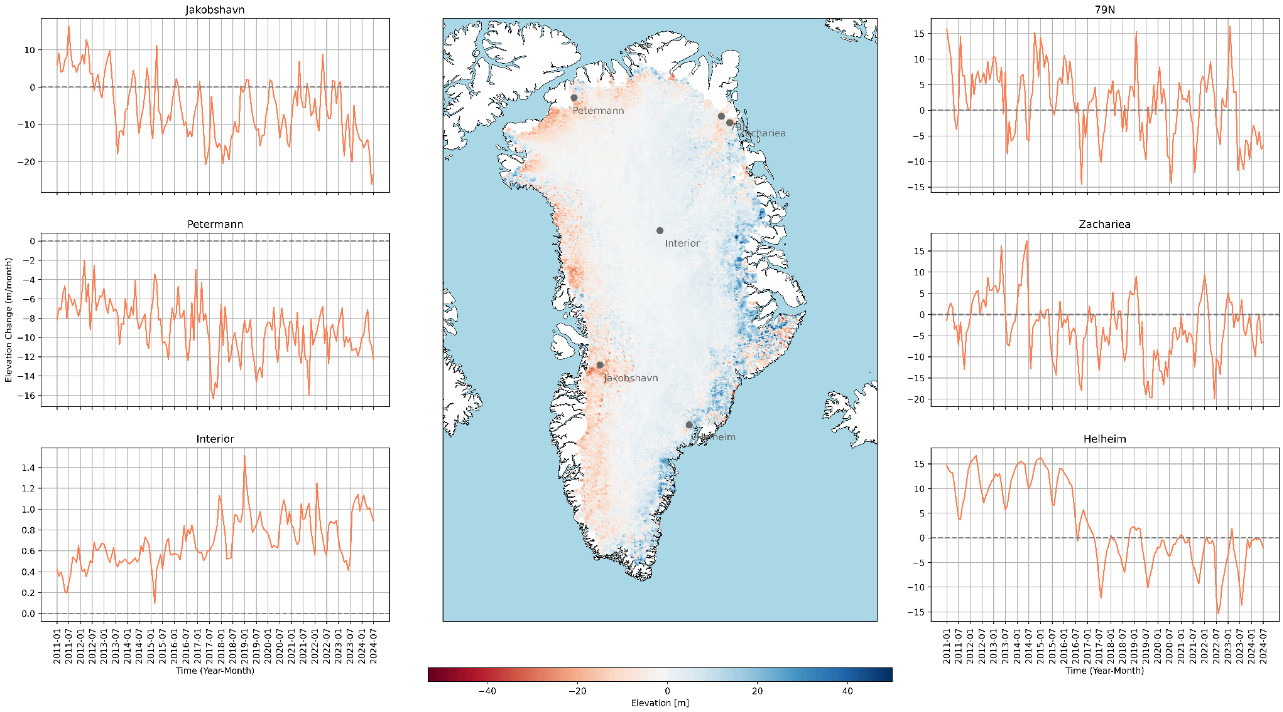

Figure 1: The map in the middle shows the surface elevation changes over the GrIS over one month. On the map are five glaciers and one centre point marked in grey. The time series for these glaciers have been plotted on the sides.

2.2 Ice Velocity Product Reveals Subglacial Water Transport

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 interest in a time-series IV product, which would enable end-users to carry out this kind of analysis more easily.

A novel product aimed at studying the uplift/subsidence of the ice surface associated with the propagation of subglacial water has been developed. It offers a high temporal (6-12 days) and spatial (100 m) resolution. In December 2024, the first version of this product was published as part of the Greenland Ice Sheet CCI+ programme. The published product covers the full spatial and temporal extent of an event observed on the North Greenland Ice sheet in 2020 (documented in https://doi.org/10.1029/2023GL103240), illustrated in Figure 2 below. An interesting phenomenon is observed, where an uplift bulge is propagating rapidly downstream, all the while expanding and leaving in its trail a more persistent, less pronounced subsidence pattern. This could indicate a series of cascading draining events. The source of the water is presently unknown.

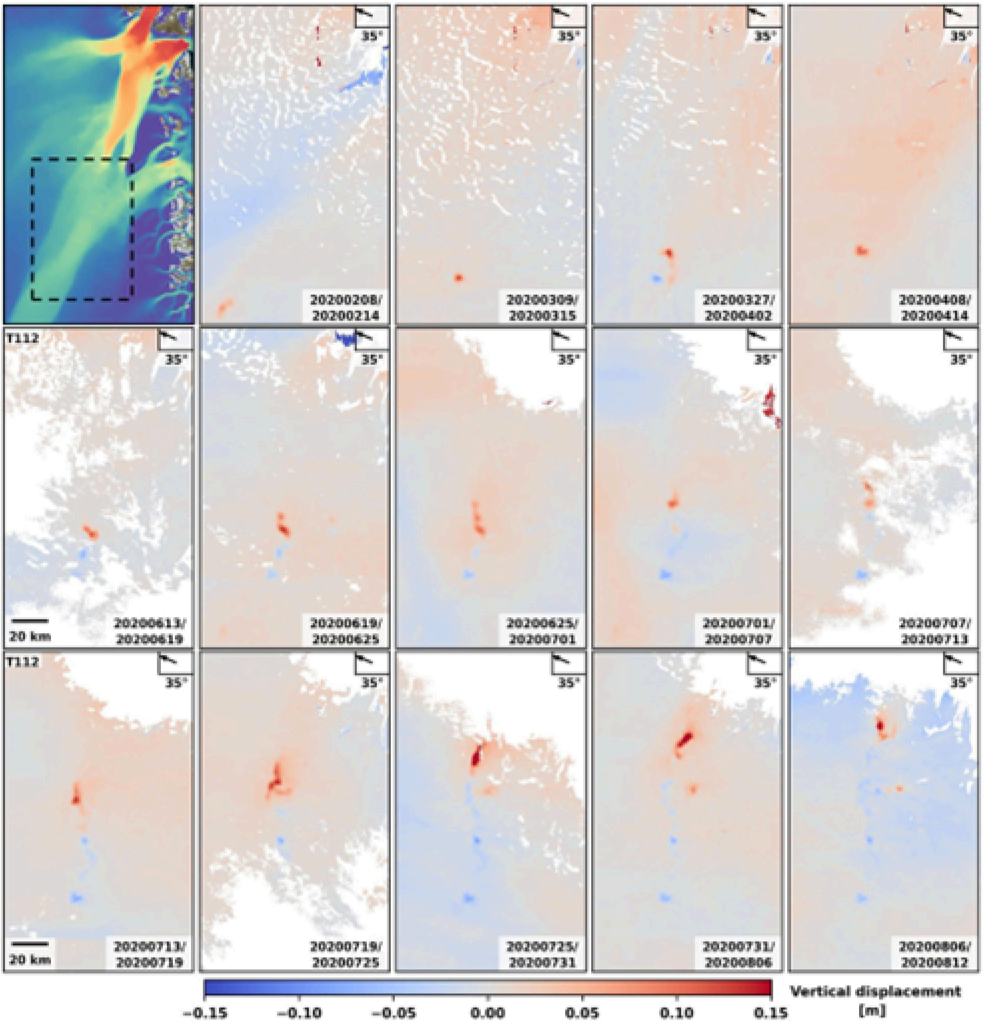

Figure 2: Uplift/subsidence observed by InSAR of a subglacial water propagation event on the North Greenland Icesheet

2.3 The Greenland ice sheet's loss is measured by gravity changes and GPS network stations

The US/German GRACE (2002-2017), and GRACE-FO (2018-) missions 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). The CCI GMB data produced consists of a monthly time series of basin-averaged ice mass changes for different drainage basins of the Greenland Ice Sheet and the entire ice sheet. For 2003 – 2024, the GRACE-derived mass change time series reveals distinct mass losses for all drainage basins under investigation. The average mass loss for the Greenland ice sheet in the GRACE period 2002-24 is around -255 GT/year, corresponding to a global sea level rise of 0.7 mm/year.

However, recently a new approach that uses the whole GNSS[(1)] network as a "virtual instrument" has been developed and published (Barletta et al. 2024), and it is capable of measuring the total ice loss from Greenland at daily resolution. The method has been compared and validated with existing (ESA CCI DTU GMB) monthly mass balance estimate techniques (Figure 3). This new GNSS-derived mass balance allows us to close the 2017-18 data gap between the GRACE and GRACE-FO missions. By combining this new technique and the GRACE-derived GMB, a novel constraint has been found on both the mass variations and glacial isostatic adjustment (GIA) models. It has been verified that GIA models only accounting for the deformation caused by the last ice age are not able to explain the observed vertical deformation rates.

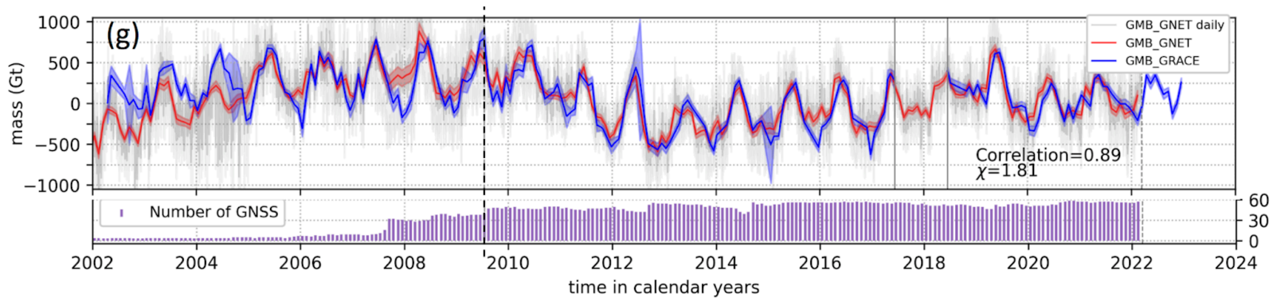

Figure 3: Greenland GPS network measures the daily ice sheet's weight loss. Detrended monthly mass variations derived from GRACE (gravity variation) in blue and from GNSS network in red. The daily mass variations derived from the GNSS network are in grey. In violet the number of GNSS values available with time. This figure is from Barletta et al., 2024.

The time series for both approaches shows large multi-year changes, in accordance with climatic changes, with 2012 and 2019 being record melt years. The multi-year changes are quite varying, where the overall melt of the GIS showed an anomalous "slow-down" in 2013-18, in connection with relatively colder summer periods.

(1) The GNSS is a satellite constellation, which includes the most known (USA) GPS satellites.

2.4 MFID product has been updated

The Mass Flow rate and Ice Discharge (MFID) ECV product captures the solid ice mass loss of major glaciers flowing from the Greenland ice sheet and entering the surrounding fjords and oceans (Fig 4). 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). 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 updated in Phase 2 to use the 2019 surface elevation from PRODEM (Winstrup et al., 2024) and the thickness changes are 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. 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 the Greenland ice sheet.

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. 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.

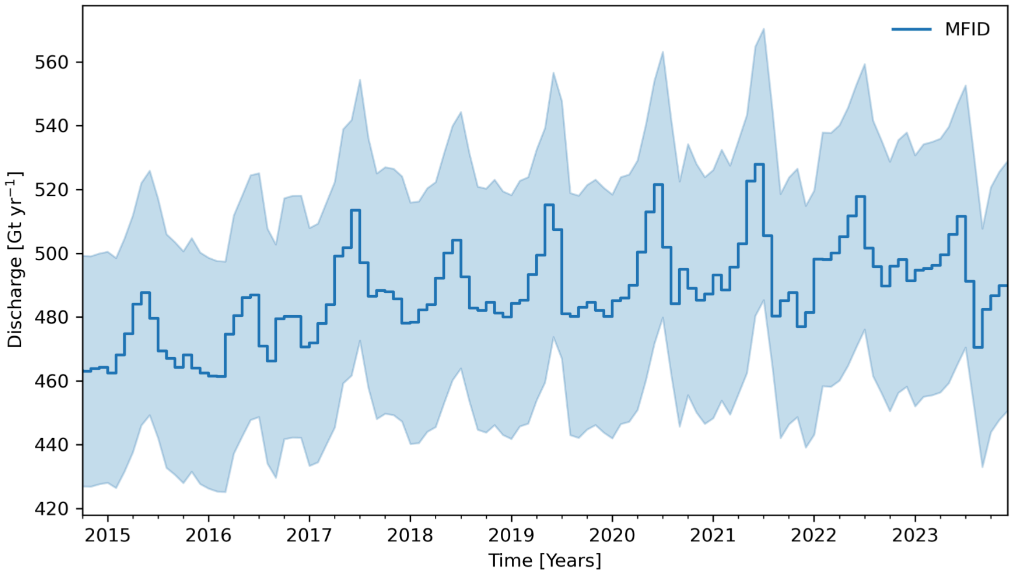

Figure 4: The MFID results for CCI+ Phase 2, showing the derived mass loss in Gt due to the flux of ice to the ocean.

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 5. The total discrepancy amounts to approximately 5 Gt/year, equivalent to about 1% of the total discharge. We anticipate that this effect will become more pronounced in future updates when monthly surface elevation changes from this phase of the CCI are integrated.

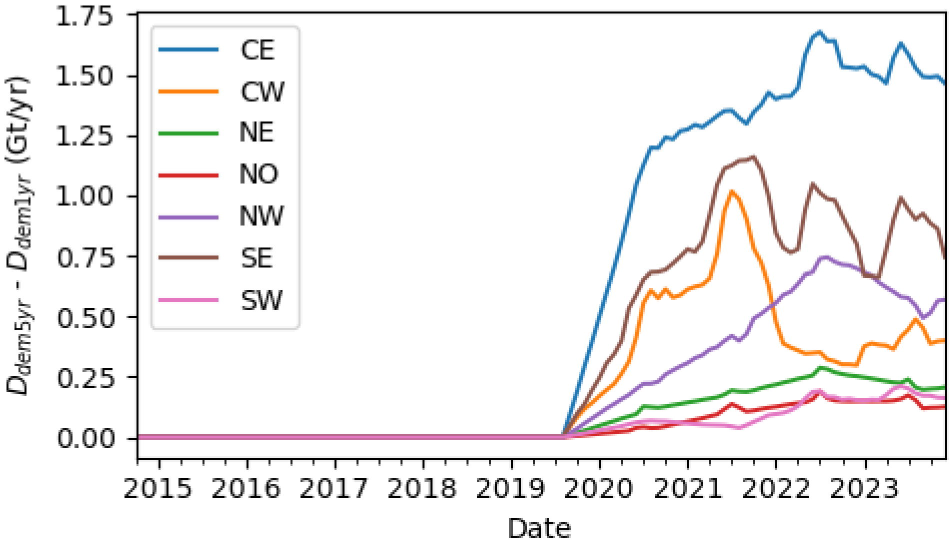

Figure 5: The difference in MFID between annual varying DEMs from 2019 or 5-year averages.

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.

- CCI Greenland website on the Climate Office website.
- ESA CCI common open data portal.
- CCI Greenland data portal.

  IMPORTANT NOTE - From November 2024 newly generated products can only be found on the websites of the Partners:

  - 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

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