

ESA Climate Change Initiative (CCI+)

Essential Climate Variable (ECV)

Greenland_Ice_Sheet_CCI+ (GIS_cci+)

Product Specification Document (PSD)

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Change Log

Issue	Author	Affected Section	Reason	Status
0.1	LS, RF	All	Document creation.	Working document.
0.2	EO team	All	Document update.	First draft.
0.3	S[&]T AS	All	Minor revisions.	First draft delivered to ESA.
0.4	JL	All	Minor revisions.	
1.0	RF	All	Major revisions based on ESA input	Second draft to ESA
1.1	S[&]T AS	All	Minor revisions.	Delivered to ESA 2012-08-29.
1.2	J. Boncori	1.4, 3, 7.2	Revisions to IV sections	Delivered to ESA 2012-08-31.
1.3	S. B.Simonsen	2.3	Update on CCN for CryoSat-2	Released to ESA on 2015-09-10.
2.0	K. Hauglund L. Sørensen	Format, doc.id. etc. §1 §6 The GMB Product	Update to Phase 2 project and format. Included text for ref. to Phase 2 contract and SoW and introduction of GMB Updated applicable and reference documents Added section 7 for the new parameter GMB	Released to ESA on 2015-10-29.
2.1	R. Forsberg	§7	Added more detailed description of GMB-product overview and specification summary.	Released to ESA on 2015-12-28
2.2	K. Hauglund T. Nagler L. Sørensen	1.2 2.2 5 7	Updated RD list Updated CFLglaciers to 28 in Table 2.1 and updated Figure 2.2. Updated section 5 on CFL Updated section 7 on GMB product file description	Released to ESA on 2016-06-20

2.3	L. Sørensen R. Forsberg D. Fantin S. B. Simonsen A. Solgaard D. Fantin A. Groh	All 9 removed 1.3 2.1, 2.2 and all 2.2 3 4 4.2.2 7	Made revisions/corrections for all sections. Sec. 9 was deleted since not relevant Added ref. 17 and 18 Updated per Year 2, minor updates through all Updated Table 2-1 with Optical IV data Revised SEC product overview Added info on 2 nd phase activities for IV production New §4.2.2 for Optical IV Modified the GMB product overview and Updated to include TU Dresden GRACE GMB product	Released to ESA on 2017-03-20
3.0	C. Hvidberg L. Sørensen D. Fantin S. H. Larsen J. Wuite S.H. Larsen	All Chapters 3-7	Made revisions/corrections in all sections, according to GIS_cci+ phase 2 documents. Deleted chapters on GLL and CFL. Inserted chapters on MFID, SGL Updated the product description.	Released to ESA 2023-05-17
3.1	D. Fantin C. Hvidberg	Minor edits in all sections	Updated according to review by A. M. Trofaier	
4.0	L. Sørensen	Added section on dSEC	Updated for Phase 3	Released to ESA

Acronyms

Acronyms	Explanation
ALS	Airborne Laser Scanner
ATBD	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CFL	Calving Front Location
CS2	CryoSat-2
CSR	Center for Space Research, University of Austin
DEM	Digital Elevation Model
(D)InSAR	(Differential) Interferometric Synthetic Aperture Radar
DMI	Danish Meteorological Institute
DLR	German Aerospace Center
DTU-N	DTU Microwaves and Remote Sensing Group
DTU-S	DTU Geodynamics Group
ETAD	Extended Timing Annotation Dataset
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
FM	Frequency Modulation
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
OT	Offset tracking

1 Introduction

This document is the Product Specification Document (PSD) updated for Phase 3 of the “Greenland_Ice_Sheet_cci+” (GIS_cci+) project in accordance with the Contract [AD1] and the Statement of Work (SoW) [AD2] with Annex B [AD3].

This PSD document is hence updated as described in the Technical Proposal of Phase 3 of the GIS_cci+ [RD1]. It is based on the GIS_cci+ Phase 3 User Requirement Document (URD) [RD2], and developed from the GIS_cci+ Phase 2 PSD document [RD3].

The PSD document is part of the deliverables in the Task 1 Requirements Analysis, with deliverable id: D1.2. The PSD is updated in two iterations, starting in Year 1 and Year 2 of the Phase 2 project, respectively, as described in the SoW Annex B [AD3]. This PSD is prepared in the first iteration of Task 1.

1.1 Purpose and Scope

The objective of the PSD is to translate the user requirements described in the URD into a complete and consistent set of product specifications, with some degree of trade-off between ideal and practical implementations.

The project will produce data products based on satellite sensors for the Greenland Ice Sheet (GIS) Essential Climate Variable (ECV). The project will produce the following ECV products:

- 1) Surface elevation change (SEC) – gridded data from radar altimetry (RA)
- 2) Ice velocities (IV) – gridded data from synthetic aperture radar (SAR) interferometry and feature tracking
- 3) Gravimetric Mass Balance (GMB) – gridded data from gravimetry and time series
- 4) Mass Flow Rate and Ice Discharge (MFID) – time series from marine outlet glaciers

In this document, each of the ECV products is described in detail, including geophysical parameters, spatial and temporal coverage and sampling, formats, quality flags, product grid and projection, annotation data, ancillary data, and error budget.

As foreseen, the URD describes a number of product requirements wanted by the users, which cannot be provided by the project due to limitations in the EO data and/or the techniques to be used. In the PSD, the decision on how user requirements are translated into product specifications will be documented. If a user requirement cannot be met, it is described why this is the case. We will define products that are as compliant as possible with both user needs and technical possibilities.

1.2 Document Structure

In this document, the five ECV product specifications are described separately. Full specifications of the sensors and the data that are used in the product generation are described in the Data Access Requirements Document (DARD).

This document is structured as follows:

- Chapter 2 provides background and parameter information, including an overview of the suggested grid and time spacing for the ECV parameters, based on the URD, as well as an indication of the added scientific value provided by the ECV products, and it provides an overview of the general formats and auxiliary data.
- Chapter 3 describes the SEC product specifications.
- Chapter 4 describes the IV product specifications.

- Chapter 5 describes the GMB product specifications.
- Chapter 6 describes the MFID product specifications.
- Chapter 7 contains a list of references.

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
AD3	DTU-ESA-GIS-CCI-P3-PROP-00 1	CCN5 FOR PHASE 3 (2025-2026) Technical, Management,Implementation and Financial Proposal (PROP)	2025.05.30	2.0

Table 1.2: List of Reference Documents

No	Doc. Id	Doc. Title	Date	Issue/Revision / Version
RD1	ST-DTU-ESA-GIS-CCI+-P2-CNN- PROP	Technical Proposal of GIS_cci+ Phase 2	2022.10.10	1.0
RD2	ST-DTU-ESA-GISCCI+-URD-001	User Requirement Document (URD) for GIS_cci+	17/05/2023	3.0
RD3	ST-DTU-ESA-GISCCI+-PSD-001	Product Specification Document (PSD) for GIS_cci+ Phase 1	17/05/2023	2.3
RD4	ST-DTU-ESA-GISCCI+-ATBD-00 1	Algorithm Technical Baseline Development (ATBD)	26/10/22021	2.0
RD5	ST-DTU-ESA-GISCCI+-PUG-001	Product User Guide (PUG)	25/02/2022	2.0
RD6	ST-DTU-ESA-ISCCI-URD-001	User Requirement Document (URD) for ISCCI	29/05/2012	1.0

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

2 Background and parameter information

2.1 Background and scientific added value

The ECV products included in the GIC_cci+ Phase 3 project represent a selected set of ECV products, with a special focus on utilising ESA mission data to the fullest extent for climate modelling and ice sheet monitoring. Additional satellite measurements which can be used for ice sheet monitoring exist but are not included, e.g. microwave backscatter that can be used to detect the seasonal onset and termination of surface melting of the ice sheet. The selected ECV products do, however, create added value for the general climate modelling community and ice sheet monitoring community when products are combined.

For **SEC**, the primary Greenland Ice Sheet CCI added value is the seamless, bias-free, gridded elevation change product, processed in a transparent and consistent way, across a diverse set of different satellites FCDR's from radar altimetry satellites. This relieves the users of having to deal with different orbits, periods and cross-over difference schemes, and makes the data much more available to a larger non-expert community. The CCI+ SEC product covers a long time period (1992-) which makes it possible to detect large changes in the ECV over time. The SEC product offers the high-spatial resolution needed for regional analysis and process studies for individual glaciers. A new dataproduct dSEC provides a dataset of elevation changes with monthly resolution covering the CryoSat-2 time period (2010-present). This dataset has been developed based on the user need for increased temporal resolution compared to previous multiyear SEC trends.

IV is a fundamental parameter for characterizing the flow of glaciers and ice sheets. It provides essential information for estimating ice discharge, mass balance, and ultimately the contribution of ice masses to sea-level rise and freshwater fluxes into the oceans. In addition, ice velocity and its spatial gradients (strain rates) are key inputs for ice flow models, which aim to explain the physical processes driving change, including subglacial hydrological dynamics such as the evolution of sub-glacial drainage networks and jökulhlaups. These measurements also help infer ice thickness and improve projections of ice sheet response to ongoing climate warming. They are also valuable for identifying glacier surges, delineating ice sheet drainage divides, analyzing flow divergence, and inferring grounding line positions—that is, the transition zone where grounded ice begins to float.

A primary added value of the Greenland Ice Sheet CCI+ is to support the continued utilization of ESA SAR mission data, with an established long-term consistency in grid spacing, coverage and methodology. The added scientific value of the ESA_cci+ project is the guaranteed public availability of ESA time-series of IV, independent of short-lived project-based efforts. The temporal and spatial coverage of the Greenland Ice Sheet derived from Sentinel-1 data within the Greenland Ice Sheet CCI is unprecedented and represents a great added value to the scientific community. Long-term, systematic, and continuous ice velocity observations are crucial for detecting interannual variability and long-term trends in ice flow. Such changes may indicate evolving boundary conditions, dynamical imbalance, or act as early warning signals of ice sheet instability and potential ice shelf collapse.

Beyond these applications, ice velocity data are widely used to monitor iceberg calving. In connection with the recent increased melting of the Greenland ice sheet, major outlet glaciers have increased in speed, accompanied by a corresponding increase in iceberg production. Icebergs are a major hazard both to navigation as well as oil and gas exploration, and thus of large societal interest in Greenland.

For **GMB**, the main advantage is that it is based on GRACE data, which is the only sensor to directly measure mass change (or equivalent sea-level rise.). An added value by the GMB product is its monthly resolution, and that it is generated to be consistent with the other ECV products derived, e.g. mass trend grids are provided for the same temporal intervals that the SECs are provided. This makes direct comparisons much easier for the end user.

For **MFID** ECV product, the main added value is that it provides an overview of the state of key marine outlet glaciers of the Greenland Ice Sheet. The product is derived from the IV product together using ancillary data together with

glaciological models to obtain the ice discharge for the largest outlet glaciers in Greenland. The added value of this data product is that it is a derived high-level product developed for more general purposes by a wider group of non-specialist users. This product can be directly used to assess the state of the outlet glaciers without specialist glaciological knowledge.

2.2 Format and sampling of the ECV products based on user requirements

A user survey was performed for the first phase of the initial Ice_Sheets_cci, and the questionnaire was prepared and circulated in March 2012 [RD6]. A total of 53 persons answered it, roughly equally divided between modellers, glaciologists, and remote sensing specialists. More than half the respondents had more than 10 years of professional experience in either science or operational/political jobs.

The table below outlines the selected basic criteria for the Greenland_Ice_Sheet_cci ECV products, as it was formulated at a Progress Meeting in Copenhagen, in April 2012, later revised and now updated for the GIS_cci+ Phase 2 project [RD2]. The update here includes the new ECV products MFID and SGL, and has excluded the previous ECV products GLL and CFL, which are not produced in this Phase 2 of the GIS_cci+, according to the Contract [AD1] and Technical Proposal [RD1]. In addition, the explorative product InSar line-of-sight uplift is included.

The selected criteria are based on a judgement between minimum and optimum spatial and temporal resolution, taking into account which EO data currently exist or is planned in connection with the Sentinel missions, and what makes a reasonable processing effort. Although the primary driver is the scientific impact (as specified in Table 2.1 below, “long-term goal”), the trade-off between costs and processing efforts is a necessary consequence of the available budget of the GIS_cci+ project.

The selected parameters are traceable to [RD2] (specifically the product overview table 3.5).

Table 2-1: Selected temporal and spatial parameters for the GIS_cci+ Phase 3 ECV products

ECV Product	Spatial resolution	Temporal resolution	Period (long-term goal)	Spatial and temporal coverage, cci+ Phase1/Phase2	Satellite sensors
SEC	5 km grid	1 per year ¹	1991-present	All ice sheet, 1991-2026	ERS-1, ERS-2, Envisat, CryoSat-2
dSEC	5 km grid	Monthly	2011-2025 (1992-present)	All ice sheet, 2011-2025	CryoSat-2
IV	250 m grid	6-12 days	2014-present	Time series of coastal margin 2014-present	Sentinel-1
	100 m grid (50m upon request)	Seasonal	2024-2025	Jakobshavn, Upernavik, Petermann, Kangerlussuaq, Hagen, Helheim, 79fjord, Zachariae, Storstrømmen	Sentinel-2
InSAR uplift rate / SAR Line-of-Sight Velocity	100 m grid	6-12 days	2016-Present	Jakobshavn area, NEGIS	Sentinel-1
GMB	50 km	1 per month	2002 - present	All Greenland	GRACE/GRACE-FO

¹For the CryoSat-2 data based products, both a 2 and 5 year running averaging will be available. In CCI+ phase 2 time-series may be provided as an auxiliary data set in the CryoSat-2 observational period.

MFID	N/A	Monthly (across basins)	2014-present	Greenland ice sheet	Sentinel-1A/B (and ancillary data)
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Comments on the selections:

SEC – A user required a minimum spatial resolution of 1-5 km. 1 km radar altimetry data do not make sense presently or for Sentinel-3 due to the wide spacing between the ground tracks. 5 km was selected as a reasonable trade-off between the beam footprint and the width of the ice streams.

For the GIS_cci+ phase 2 emphasis will be on increasing the temporal resolution of the SEC product. This will support e.g. C3S.

IV – An optimal spatial resolution in URD at 50 m, minimum at 100 m-1 km. 250 m was selected as a trade-off giving a reasonable mapping with several pixels across most outlet glaciers. The temporal resolution is set to annual with sub-yearly resolution time series produced on two major glaciers. It can, additionally, be sub-annual (even monthly) for some periods, and less than annual for other years due to data gaps. The reader is referred to the DARD [RD4] for temporal coverage plots.

GMB - The user required optimum resolution in time of 1 month, and in space of 50km.

MFID - The MFID is a high-level product based on both satellite sensors and auxiliary data. An ensemble of nine large key outlet glaciers is chosen for the GIS_cci+ project. The spatial and temporal resolution is constrained by the IV data used to generate the product.

2.3 Basic grid and line formats – NetCDF, shapefiles and ASCII

The user community was in good agreement with the CCI general recommendations:

1. Grid files (e.g. SEC, IV) to be stored in *NetCDF format*. IV files to be stored as Cartesian velocity components (i.e., north and east velocity in m/d) [URD section 4.6]. We suggest using the widespread NetCDF-4 version, readily supported by MATLAB, GMT and Python. See: <https://unidata.github.io/netcdf4-python/>
2. Line files (e.g. GLL) to be stored as *Shapefiles*. About 1/3 of the respondents reported preferring GIS formats [URD Q46], and NetCDF for the line is awkward and not suitable for many users. This ensures a useful consistency with the glaciers CCI project, which also maps outlines of isolated Greenland glaciers. See <http://www.esri.com/library/whitepapers/pdfs/shapefile.pdf>.

2.4 Map projection for grid data

The preferred map projection for the SEC and IV grids is the Polar Stereographic as indicated by more than 50% of user questionnaire respondents [URD p. 17]. This projection has the advantage of a simple implementation and being a conformal projection, however otherwise is not very suitable in Greenland, due to large-scale distortions from north to south (as much as 7%). This applies whether a standard parallel of scale 1 is used or not.

UTM grids are conformal, too, and are much better in terms of area distortions with zone 24 usually used in most mapping projects. However, although more than 40% indicated UTM as their preferred projection, many non-GIS/non-geodesy users are not used to working with it. Furthermore, UTM is not suitable for Antarctica, where SCAR conventions for polar stereographic parameters are in place. Also, climate modellers seem to never use UTM.

Geographic grids (latitude and longitude) have been used in several satellite altimetry studies (e.g., Wingham et al 1998; Khvorostovsky; Davis et al, 2005), and could be an option since the satellite orbits are denser in the north, and therefore support the denser sampling in longitude due to the meridian convergence. Geographic grids were indicated as preferred by 44% of the users. However, for modelling use, general isotropic uniformity of results and errors, and more lean storage and handling of data, we prefer to implement the ECV products in standard map projections. Also, IV vectors represented in Lat/Lon grids would be unpractical for plotting and visualization in the north, where the longitudinal spacing would be denser than in the south.

Stereographic projections used for public domain data sets include both data with reference parallel 70N and 71N (e.g., US ICESat DEMs and Ian Joughin SAR IV data sets), with some consensus on the use of a reference longitude of 45W.

With simplicity and most common use in mind, we make the convention for the following GIS-cci/cci+ standard projection:

Polar stereographic, reference latitude 70N, reference meridian 45W, ellipsoid WGS84

This makes the reference parallel central in latitude on the Greenland ice sheet. The scale factors, i.e. the factor with which small true distances must be multiplied to obtain projection grid distances, for this projection, are the following:

<i>Latitude</i>	<i>Scale factor, standard polar projection</i>	<i>GIS_cci projection</i>
<i>82N</i>	<i>1.005</i>	<i>0.975</i>
<i>70N</i>	<i>1.031</i>	<i>1</i>
<i>60N</i>	<i>1.072</i>	<i>1.040</i>

It should be noted that a full geodetic ellipsoidal implementation of this projection is necessary; spherical approximations are not accurate enough to match the resolution in Table 1. GIS software as well as ENVI should handle such a transformation properly; detailed public domain routines are available, for more info and links see e.g. http://earth-info.nga.mil/GandG/publications/tm8358.2/TM8358_2.pdf. Since the start of the CCI project, this projection EPSG code 3413) is now the preferred projection for datasets used for modelling purposes in Greenland (e.g. by the IPCC's Ice Sheet Modelling Intercomparison Project (ISMIP)), and standardised across major data repositories, as e.g. NSIDC (National Snow and Ice Data Center, US).

2.5 File naming conventions

The Greenland Ice Sheet CCI ECV products will follow the standard file naming convention of the CCI products.

3 The SEC product

3.1 SEC product overview

Surface elevation changes of an ice sheet are directly linked to the atmospheric forcing and hence climate changes. The GIS-CCI SEC is derived from radar data, and therefore, the product is the elevation change of the reflecting surface rather than the snow surface, depending on the application of a suitable backscatter correction or not. The SEC product has been evaluated in several publications, e.g. [Sørensen et al. (2015)].

There is a fundamental problem in the definition of the SEC product: Which temporal and spatial filtering should be used to define the SEC, defined as dh/dt in units of m/yr [GCOS (2022), Table 1; AD2(SoW), p. 12] Clearly, daily or monthly SEC only represent spurious snowfall events as well as the yearly cycle; yearly averaged SEC is difficult to estimate, due to data constraints. A very long temporal averaging, e.g. since the beginning of the RA time series (1991), does not make sense either as the Greenland ice sheet is known both from GRACE, ICESat and mass balance studies to display significant changes over the course of a few years. Based on these considerations, SEC grids are based on 5-year running means of RA data, except for the CryoSat-2 time period, where also 2-year means are provided.

For the SEC grids based on conventional RA data, the highest-sloping areas of the ice sheet cannot be monitored due to the surface-slope relocation of the measurements. Therefore, SEC estimates are provided only for grid points with a surface slope of less than 1.5 degrees.

3.2 Background on product generation

The SEC FCDR from the individual satellite records is available in the level-2 Geophysical Data Records (GDR's). For SEC the GDR's will be the primary source of information, as standardised re-tracking algorithms will be applied in other projects and processing streams (notably the FDR4ALT data)

The actual algorithms used for SEC are outlined in the ATBD [RD4], and were chosen based on results of a round-robin [Levinsen et al. (2016)]. However, the SEC (surface elevation change) in units m/yr, is subject to time-filtering (and weakly spatial filtered) trend parameter, filtered on a tentatively 5-year moving average basis, and the gridding of the line- or cross-over oriented results of SEC are derived from an optimal least-squares estimation (also known as Kriging or collocation). The method is widely used in geodesy and geophysics and readily allows the estimation of both the predicted value and its standard deviation. The method is based on estimating an empirical covariance function $C(s)$ from the data (after long-wavelength de-trending), where s is distance, and then obtaining estimates of predicted signal s_{pred} and variance σ^2 by solving of the linear equation for a selected set of neighbour observations \underline{x} by

$$s_{pred} = C_{sx} C_{xx}^{-1} \underline{x}; \sigma^2 = C_0 - C_{sx}^T C_{xx}^{-1} C_{sx}$$

where C_{xx} and C_{sx} are auto- and cross-covariance matrices between observation vectors \underline{x} and the signal s .

Details of the method, often described with quite different names for essentially the same mathematical concepts (e.g., semivariogram instead of covariance function), may be found in numerous textbooks such as e.g. [Heiskanen and Moritz (1967)]. The method may be expanded by allowing a certain degree of smoothing, based on the a-priori assumptions of noise in the pointwise surface elevation differences.

Some epochs may be missing depending on the data availability. Because of the relatively sparse track spacing, especially in southern Greenland, grid cells might be totally void of data, and some degree of interpolation will be necessary. The spatial error covariance function of the SEC will be used to set up rules for when to set a grid cell as "missing data" or interpolate it from nearby satellite observations.

For CryoSat processed data, the above merging algorithm is not used. CryoSat data are estimated directly from dh/dt regression across 1 km-resolution cells, and averaged into 2-year and 5-year running means, for details see the ATBD.

3.3 Detailed SEC product specifications

File format

NetCDF files containing each grid GIS-CCI polar stereographic grid covering the entire Greenland ice sheet

Greenland geographic limits: all ice and land areas: 59-84N, 73-11E

Polar stereographic limits: northing -3300 to -700 km, easting -650 to 850 km

Spatial and temporal Resolution

5 km, 5-year and/or 2-year means (CryoSat only).

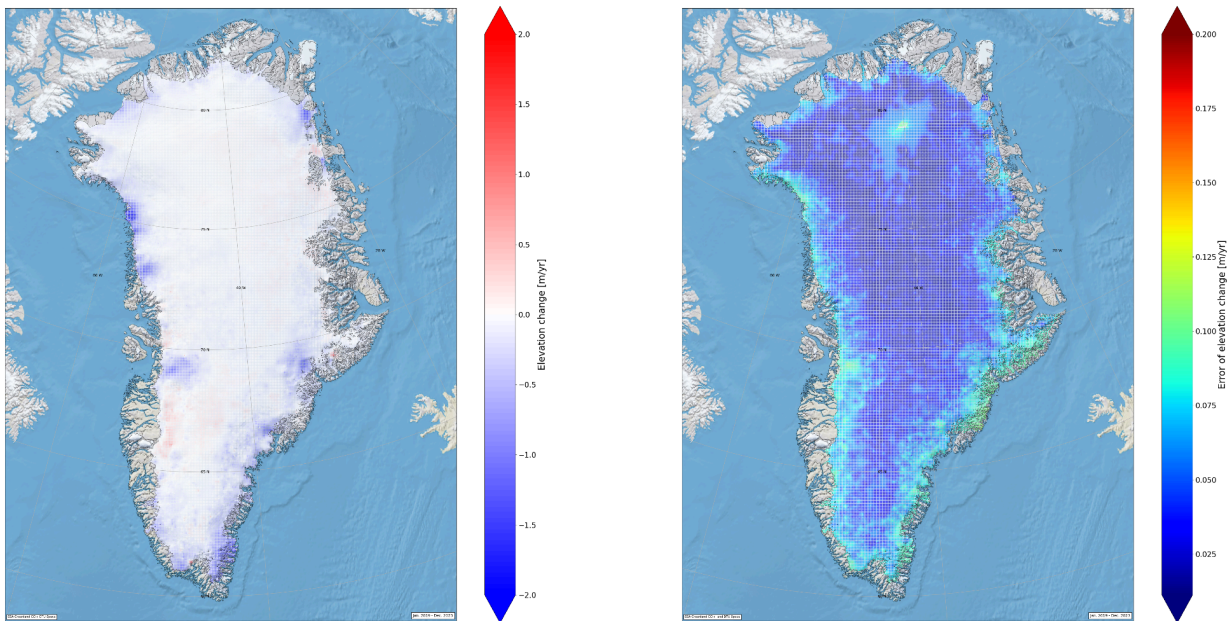


Figure 3.1: Left: SEC derived for Greenland at 5km grid from 2019-2023. Right: The error associated with the derived SEC from 2019-2023.

Global NetCDF attributes

This is the basic metadata for the SEC product. For ASCII versions, a similar header is output.

Global Name	Attribute	Data Type	Description
Title		String	A descriptive title for the SEC dataset
Grid_projection		String	Defining parameters for the map projection used
Time		Float	Midpoint time of acquisitions used (Hours since 1990.01.01)
Start_time		Float	Time of first observation (Hours since 1990.01.01)
End_time		Float	Time of last observation (Hours since 1990.01.01)
Lat		Float	Latitude in decimal degrees north, range -90 to +90.
Lon		Float	Longitude in decimal degrees east, range -180 to +180.
SEC		Float	Surface Elevation changes, smoothed
SEC_error		Float	Error estimates associated with surface elevation changes

Global Name	Attribute	Data Type	Description
X		Float	Cartesian x-coordinate- easting
Y		Float	Cartesian y-coordinate - northing

Variables in grids

In case of ASCII grids, these data are more compact as space and time parameters are given in the grid header. For the NetCDF format, the basic parameters would be:

Field name	Type	Description
Northing	Float	N-coordinates of centre of grid cell (m)
Easting	Float	E-coordinates of centre of grid cell (m)
Time	Float	Time of grid cell observation (decimal years)
SEC	Float	Surface elevation change long-term trend, m/yr, running 5-year mean
SEC_error	Float	Estimated error of SEC
no_observations	Logical	Flag for values on land or too far away from data points
Grid_observations	Int	Number of GRD data points in grid, used in gridding. This is a crude and useful proxy for errors and useful for masking out interpolation results if needed.
Landtype	Int	Land type definition for the applied grid

Note: The “average” for the geophysical corrections at the grid cell level means the averaging of all corrections in the GDR, passed through the same algorithm to generate the SEC.

3.4 Detailed dSEC product specifications

3.4.1 dSEC product overview

The dSEC product represents gridded surface elevation change derived using a spatio-temporal state-space model. The resulting data product for dSEC resolves continuous monthly variability by combining spatial correlations and temporal dynamics within a unified framework.

The product reflects elevation changes and captures both seasonal variability and long-term trends, while accounting for irregular sampling and observational uncertainties.

3.4.2 Background on product generation

The dSEC product is generated from satellite altimetry observations mapped onto a regular grid covering the study area. Each observation is assigned to a grid cell based on its spatial location, and observation times are discretised into consecutive time steps.

Spatial dependencies between neighbouring grid cells are represented using a Gaussian Markov random field (GMRF), defined through a sparse precision matrix based on a four-neighbour connectivity structure. Temporal evolution is modeled as a first-order autoregressive (AR(1)) process, ensuring temporal continuity while allowing for short-term variability.

Observations are linked to the underlying spatio-temporal field through a Gaussian observation model, which accounts for measurement noise and unresolved variability. The full model is formulated as a state-space system and solved using maximum likelihood estimation, where the elevation-change field is treated as a latent variable.

This approach allows simultaneous estimation of the gridded dSEC field and associated uncertainties, without relying on predefined seasonal models. As a result, the product provides a continuous, monthly-resolved representation of surface elevation change, capturing both seasonal signals and long-term trends while accounting for data gaps and irregular sampling [Andersen et al., 2025].

3.4.3 Detailed dSEC product specifications

File format

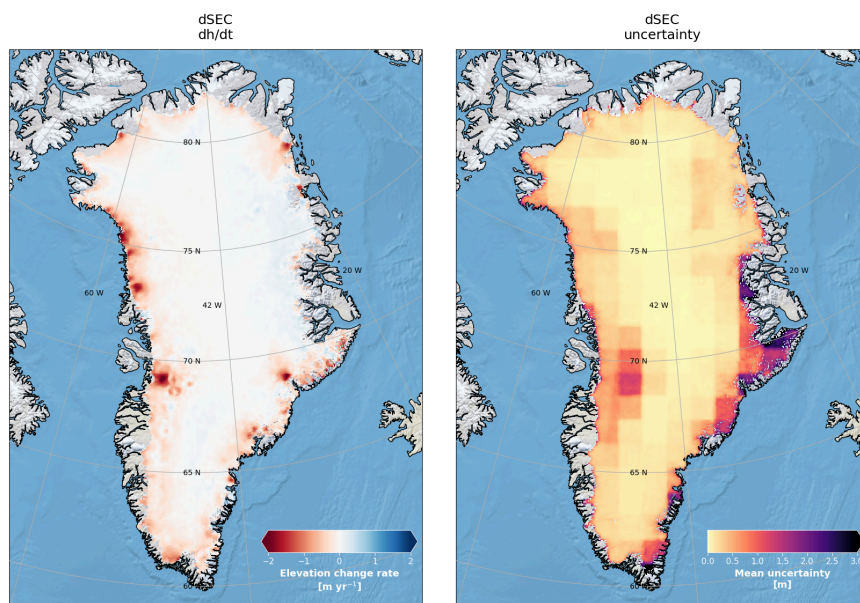
NetCDF files containing gridded dSEC fields on a polar stereographic grid covering the Greenland Ice Sheet.

Spatial and temporal resolution

5 km spatial resolution with monthly temporal resolution.

Figure

Example of dSEC (left) and associated uncertainty (right) for a selected time period.



Global NetCDF attributes

Global Attribute Name	Data Type	Dimensions	Description
Title	String	-	A descriptive title for the dSEC dataset
Grid_projection	String	-	Defining parameters for the map projection used
Time	Float	(time)	Time in datetime format
Lat	Float	(lon,lat)	Latitude in decimal degrees north
Lon	Float	(lon,lat)	Longitude in decimal degrees east
ZZ	Float	(time, y, x)	Surface Elevation changes, smoothed (m)

Global Attribute Name	Data Type	Dimensions	Description
ZZ_er	Float	(time, y, x)	Elevation change uncertainty (m)
I	Float	(x,y)	Reference elevation (m)
X	Float	(x)	Cartesian x-coordinate- easting
Y	Float	(y)	Cartesian y-coordinate - northing

4 The IV product

4.1 IV products overview

The Ice Velocity (IV) products produced in Greenland Ice Sheet CCI+ contain gridded surface velocity maps of the Greenland Ice Sheet that are derived from repeat-pass synthetic aperture radar (SAR) data using combinations of offset tracking (OT) and InSAR as well as optical data (OT only). A velocity grid represents the average ice surface velocity for the selected period of the image pair or merged image mosaic. The product specifications are guided by the GCOS 2022 (Global Climate Observing System) targets for the Ice Sheets Essential Climate Variable (ECV), and it can be noticed that the reference for the GCOS requirements for IV is the Phase 1 URD [RD6].

4.2 Background on product generation

4.2.1 SAR IV product

The primary processor for SAR IV generation is the ENVEO software package (ESP v2.1). ESP is a state-of-the-art IV retrieval algorithm designed for SAR sensors and has been tested rigorously through intercomparisons with other packages and extensive validation efforts. The main production line applies advanced iterative offset tracking techniques utilising long stripes of Sentinel-1 (S1) C-Band SAR data acquired in interferometric wide (IW) swath mode to generate time series of ice velocity maps (Wuite et al., 2025; Nagler et al., 2015). These velocity maps cover all areas (tracks) with repeat-pass S1 acquisitions (6/12-day) in Greenland. The 6- and 12-day velocity maps serve as inputs for generating monthly and annual ice velocity products covering the entire Greenland Ice Sheet. The annual datasets are produced for the Copernicus Climate Change Service (C3S) and are made available through the C3S Climate Data Store (CDS).

S1 derived IV retrieval over the Greenland Ice Sheet margins is continued in this phase of the project to cover all the areas required for the product on MFID. Additionally, in this phase of the project the IV processing chain is upgraded to accommodate the Extended Timing Annotation Dataset (ETAD) products.

The ETAD product provides a timing correction of the S1 SAR products, that is based on modelling and ancillary data. A significant source of velocity error arises from uncompensated propagation delays, particularly those caused by the troposphere and ionosphere, which can be misinterpreted as ice motion. The uncorrected phase delays and the approximations used during the formation of a SAR image result in an inaccurate timing of the radar signal. Since the grid sampling in a SAR image is defined by the azimuth (slow time) and slant-range acquisition time (fast time), timing errors result in inaccurate positions in the SAR image. To address these and other biases, offset tracking (OT) results are typically calibrated during postprocessing using stable or slow-moving reference areas, such as rock outcrops or ice divides. However, calibration is challenging in regions lacking stable reference points or in situ measurements, such as tracks confined to the interior of ice sheets. In such cases, ETAD products offer a valuable alternative, by including the following corrections:

- Tropospheric delay correction (range timing correction)
- Ionospheric delay correction (range timing correction)
- Correction of solid-earth tidal effects (range and azimuth timing correction)
- Bistatic bias correction (azimuth timing correction)
- Doppler range shift (range timing correction)
- Frequency Modulation (FM) mismatch correction (azimuth timing correction)

The benefits of this upgrade will be demonstrated by generating a Greenland Ice Sheet wide ice velocity map entirely based on ETAD data. The generated product will be used to explore how the timing delay corrections mitigate biases in OT IV measurements and affect the mass flux ice discharge estimation.

4.2.2 Optical IV product

The ECV optical IV product is generated from offset-tracking applied to Sentinel-2 data. This is mainly due to the robustness of this type of technique. The feature tracking algorithm takes a pair of optical images of the same region of interest. Had the pair of images coregistered and pre-processed, the images are gridded, with one image designated as the *reference* image, and another the *search* image. When setting up a grid of a given grid spacing (e.g., a grid point at every 10 pixels), the algorithm will try to find the region of maximum correlation of the reference image within the search image.

During the generation, all the sources of East and North Cartesian velocity components are derived and re-sampled to the output grid. Subsequently, all the generated IV maps are merged into a single map. An IV map will only be added if the RMS is below a given threshold. This results in the generation of a seasonal product with one or more gridded v_N and v_E maps in NetCDF format.

As a final remark, it should be kept in mind that the technique employed will provide results only in feature-rich and/or coherent areas.

The optical IV product contains the velocity components in the north and east directions between the input image pairs, as well as the root-mean-square (RMS) of them. The product also contains seasonal maps.

This set of 2 components allows us to calculate the magnitude of the horizontal velocity. All quantities are expressed in meters per day. The resolution of the products is 100m. A high-resolution version (50m) is available upon request.

Further details on the optical IV generation algorithm will be provided in the ATBD [RD4] and PUG [RD5].

4.2.3 InSAR uplift rate

The SAR Uplift/LoS velocity product is a prototype product containing timeseries of single-pair Sentinel-1 InSAR displacement rate measurements. The aim of this product is to provide a product with high temporal resolution tailored to study rapidly varying and transient ice uplift/subsidence phenomena, such as those associated with subglacial water transport. The product is generated using a timeseries of Sentinel-1 SLC images from the same track. For each InSAR pair, generated from acquisitions 6-12 days apart, a line-of-sight velocity map is first generated by unwrapping, calibrating and geocoding the interferogram, converting the measured displacement to velocity by dividing with the temporal separation between the two acquisitions in the InSAR pair. Once the entire time series has been generated, the pixelwise median LoS-velocity is calculated and subtracted from the individual velocity maps. The purpose of this is to remove the bulk of the horizontal ice flow velocity contribution to the LoS velocity, making observation of small-scale uplift/subsidence phenomena easier. The uplift maps are provided on a (time,x,y) grid in NetCDF file, described in the following section.

4.3 Detailed IV products specifications

SAR IV:

Products are provided as either NetCDF4 or GeoTIFF files with separate layers for the velocity components v_x , v_y , v_z and v_v (magnitude of the horizontal components). For velocity mosaic, consisting of merged velocity maps additionally maps showing the valid pixel count and uncertainty (std) are included. Table 4.1 shows the main data variables and type. Only a single time slice is provided per NetCDF4/GeoTIFF. For each file, one (x, y)-grid is supplied, and the value of the time coordinate represents the midpoint time of the acquisitions used to form the given grid. The ice velocity maps are provided on a 250 m grid in the WGS 84 / NSIDC Sea Ice Polar Stereographic North projection (EPSG: 3413, defined at <https://epsg.io/3413>). The horizontal velocity is provided in true metres per day, towards the easting (v_x) and northing

(vy) direction of the grid, and the vertical displacement (vz), is derived from a digital elevation model (TanDEM-X 90m DEM; Rizzoli et al., 2017). For all maps, a no-data value of 3.4028235e+38 is used.

Table 4.1: SAR IV main data variables and type.

Variable name	Variable description	Type
land_ice_surface_easting_velocity	Ice velocity East component [m/day]	32-bit floating point
land_ice_surface_northing_velocity	Ice velocity North component [m/day]	32-bit floating point
land_ice_surface_vertical_velocity	Ice velocity vertical component [m/day]	32-bit floating point
land_ice_surface_velocity_magnitude	Ice velocity magnitude [m/day]	32-bit floating point
land_ice_surface_measurement_count	Valid pixel count [#]	32-bit integer
land_ice_surface_easting_stddev	Easting standard deviation [m/d]	32-bit floating point
land_ice_surface_northing_stddev	Northing standard deviation [m/d]	32-bit floating point

Optical IV:

The product is provided as NetCDF4 file with separate layers for the velocity components vx, vy and vv (magnitude of the horizontal components), as well as the relative RMS. According to requests, the product may contain several products with a shorter time range, thus building up a time series. For each NetCDF4 file, the value of the time coordinate represents the midpoint time of the acquisitions used to form the given grid.

The products are generated for 9 major outlet glaciers: Hagen Glacier, Nioghalvfjerdingsfjorden Glacier, Zachariae Isstrøm, Storstrømmen Glacier, Kangerlussuaq Glacier, Helheim Glacier, Jakobshavn Isbræ, Upernavik glaciers and Petermann Glacier. The data will be available at a spatial resolution of 100m (50m upon request).

Global NetCDF attributes

The layout is inspired by the CF-Metadata conventions.

Global Attribute Name	Data Type	Description
title	string	A descriptive title for the IV dataset. Format: "GlacierName_Region_Seasonal_YYYYMMDD_YYYYMMDD"
institution	string	Institution where the data was produced. Format: "S&T Norway"
source	string	Original data satellite source. Format: "Sentinel-2 L2A"
history	string	A detailed record of processing steps and input image pairs. Format: "Created Ice Velocity(IV) pairs from [Sensor] input tiles: [Input_File_1] [Input_File_2]... Combined input_files by [Method]"
references	string	Reference to the technical documents or ATBD. Format: "DocumentID_1, DocumentID_2"
tracking_id	string	Universal Unique Identifier for the dataset. Format: "8-4-4-12 Hexadecimal UUID"
Conventions	string	The metadata conventions followed. Format: "Name-Version"
product_version	string	The release version of this data product. Format: "X.X"

format_version	string	The specific data standard version used for formatting. Format: "Agency Data Standards X.X"
summary	string	A description of the dataset glacier and date range. Format: "Ice Velocity [ProductType] of [GlacierName] from Sentinel-2 data acquired between the [YYYY-MM-DD] and [YYYY-MM-DD]"
keywords	string	Searchable tags for the dataset. Format: "comma, separated, lowercase, terms"
id	string	A unique product identification string. Format: "YYYYMMDD_Agency-Level_Project-Variable-Sensor-Resolution-GlacierName-Duration-vX.X"
data_created	string	The date the product was generated. Format: "YYYY-MM-DD"
creator_name	string	Entity responsible for data creation. Format: "Institution Abbreviation"
creator_url	string	Website for the creating entity.
creator_email	string	Contact email for the data creator. Format: "name@domain.ext"
project	string	The overarching project name. Format: "ESA Greenland Ice Sheet CCI+"
time_coverage_start	string	The start timestamp of data acquisition. Format: "YYYYMMDDTHHMMSSZ"
time_coverage_end	string	The end timestamp of data acquisition. Format: "YYYYMMDDTHHMMSSZ"
time_coverage_duration	string	The total time span in ISO 8601 duration format. Format: "P[n]DT[n]M[n]S"
platform	string	The satellite platform used. Format: "Sentinel-2"
sensor	string	The specific instrument used. Format: "Sentinel-2 MSI"
spatial_resolution	Float	The grid spacing of the product in meters. Format: "100.0"
key_variables	string	The main scientific variables in the file. Format: "land_ice_surface_northing_velocity, land_ice_surface_easting_velocity, rms_mean";"
comment	string	Technical notes on the tracking algorithm. Format: "Pixel offsets tracked using [Method]. The offsets are calculated for pairs between [Min] and [Max]"

Variable attributes

Variable's attributes are attached to an individual array, i.e. a grid epoch data

Variable Attribute Name	Data Type	Description
_FillValue	double	The value used to represent missing or undefined data.
units	string	The physical units of the measurement.
long_name	string	A descriptive name used for display labels.
description	string	A plain text summary of the variable.
standard_name	string	The CF-convention name for the variable.
grid_mapping	string	Reference to the coordinate reference system variable.

coordinates	string	The coordinate variables associated with the data.
-------------	--------	--

Variables in grids

In case of ASCII grids, these data are more compact as space and time parameters are given in the grid header

Field name	Type	Description
crs	Double	CRS of the data (EPSG: 4326)
land_ice_surface_easting_velocity	Geo2D Double	easting ice velocity m/yr
land_ice_surface_northing_velocity	Geo2D Double	northing ice velocity m/yr
rms_mean	Geo2D Double	arithmetic mean of Root Mean Square Error
time	Float	Midpoint time of acquisition used (days since 1990-01-01 00:00:00 UTC)
x	Float	x coordinate of projection (m)
y	Float	y coordinate of projection (m)

InSAR uplift rate:

The product is provided as a timeseries of grids in a NetCDF4-Classic file using CF-metadata conventions for easy ingestion into tools like QGIS, with the main variables described in the table below. The grid is sampled at a 100 m posting in the WGS 84 / NSIDC Sea Ice Polar Stereographic North projection (EPSG: 3413, defined at <https://epsg.io/3413>). Time sampling is defined by the availability of Sentinel-1 acquisitions, typically either 6 or 12 day intervals, and more, when temporal decorrelation prevents generation of coherent interferograms.

Variable	Type	Description
crs	string	Attributes of this variable describe the coordinate reference system, as per the CF Metadata convention
time	float64	Midpoint time of InSAR pair used for each map, measured in days since 1990-1-1 0:0:0
x	float64	x coordinate of projection
y	float64	y coordinate of projection
time_bnds	float64	First and last date of InSAR pair used for each map, measured in days since 1990-1-1 0:0:0
TB	float64	Temporal baseline of InSAR pair used for each map (i.e. time between first and last acquisition)
los_azimuth_angle	float32	Line-of-sight azimuth angle from local East (increasing anti-clockwise, i.e. E=0, N=pi/2)
los_elevation_angle	float32	Line-of-sight elevation angle, positive from local level towards sensor

uplift_rate	float32	Inferred vertical displacement rate derived from line-of-sight displacement, (positive up)
los_velocity_time_median	float32	Pixelwise time median of original line-of-sight velocity measurements.

5 The GMB product

5.1 GMB product overview

The twin satellites of the Gravity Recovery and Climate Experiment (GRACE) and GRACE-Follow-On (both referred to as GRACE in the following) have been measuring changes in the Earth's gravitational field since 2002. Time-variable gravity fields can be used to infer mass changes and mass redistributions in the Earth's subsystems (e.g. the cryosphere). The mass balance of the Greenland Ice Sheet (GIS) can be measured with an accuracy of around 20 Gt/yr. The Greenland Ice Sheet cci (*GIS_cci*) produces Gravimetric Mass Balance (GMB) products for the Greenland Ice Sheet from GRACE measurements. These products comprise monthly mass change time series for the entire GIS and different drainage basins as well as gridded mass change trends over different 5-year periods.

5.2 Background on product generation

GRACE data are available from different processing centres, including the Centre for Space Research (CSR) at the University of Texas, and the GeoForschungsZentrum (GFZ). For the data, we make use of the CSR RL06 which includes spherical harmonic coefficients up to degree $l_{max}=90$ (both GRACE and GRACE-FO data can be found here <https://isdc.gfz-potsdam.de/grace-isdc/>).

Monthly spherical harmonic coefficients of changes in the Earth's gravity field are available for the mission period. Different processing algorithms exist in order to derive the required information from the available data for the GIS. The round-robin (RR) exercise carried out by TU Dresden has confirmed that the *mass inversion* and *spherical harmonic filtering* methods give comparable results. Döhne et al. (2023) showed that the two approaches are even equivalent under certain conditions. Therefore, the GIS GMB setup is primarily based on the *inversion* method applied by DTU, where a direct estimate of mass changes is done in a direct least-squares generalised inverse processing. The choice of this method secures a consistency with the current Danish Polar Portal data (<http://polarportal.dk>), and a better and more explicit separation of Greenland mass changes from the mass changes from adjacent ice caps, especially northern Canadian ice caps in Ellesmere, Devon and Baffin Island. Details of the inversion method are outlined in the ATBD document [RD4]. In addition, a second GMB product based on the regional integration approach using tailored sensitivity kernels is provided by TU Dresden.

As specified in the User Requirements Document (URD), user requirements for a gravimetric mass balance product (GMB) were found through a joint user survey for the Antarctic Ice Sheet cci (*AIS_cci*). The results were adopted for the *GIS_cci*. The product requirements for the GMB product are outlined below:

Table 5.1: User requirements for ECV parameters

	GMB
MINIMUM spatial resolution	100 km
OPTIMUM spatial resolution	-
MINIMUM temporal resolution	Annual
OPTIMUM temporal resolution	Monthly
MINIMUM accuracy	20 GT/yr
OPTIMUM accuracy	-
What times are observations needed	all year

Since GRACE data are available each month, and since basin mass balance estimates are common practice, the statement of work [SoW-P2] extended the above requirements to provide monthly estimates of mass balance for both the entire Greenland Ice Sheet, and for the individual drainage basins. These products are provided in the Antarctic Ice Sheet cci as well, thus ensuring a close agreement in products for both projects, albeit with differences in algorithms.

The drainage basins used are an aggregation of those described by Zwally et al. (2011). **Figure 5-1** below shows the outline of the basins. They are also employed for the GMB RR exercise.

For further information on how the Ice sheet and the surrounding glaciers and ice caps are separated see the ATBD.

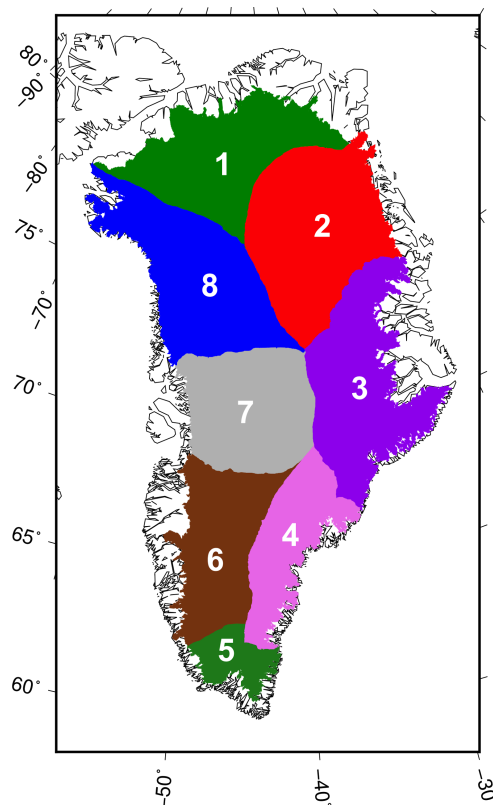


Figure 5-1: Drainage basins based on Zwally et al. (2011) in a modified way, which are used for the Basin GMB product

5.3 Product Specification Summary

The two different data products provided (mass change time series and mass trends) are described below.

Furthermore, these are provided in two versions; one generated by DTU and one by TU Dresden. The file format from the two institutes are the same, and these are described in the following. The file naming is also similar.

5.3.1 Mass change time series

The mass change time series are provided for both the entire ice sheet and for drainage each basin (Fig 7-1. Detailed information is found in the ATBD [RD4])

The time series are given in a simple ASCII format of the following form:

Time [decimal year], Mass change [GT], Error on mass change [GT]

Where *GT* is the mass anomaly in GT (relative to a chosen zero level) with the associated errors (see CECR). One file for each basin and one for entire GIS is provided, with their file names indicating content:

GIS00_grace.dat / GIS00_grace_tudr.dat: Mass change time series for entire GIS

GIS01_grace.dat / GIS01_grace_tudr.dat: Mass change time series for basin 1

GIS02_grace.dat / GIS02_grace_tudr.dat: Mass change time series for basin 2

GIS03_grace.dat / GIS03_grace_tudr.dat: Mass change time series for basin 3

GIS04_grace.dat / GIS04_grace_tudr.dat: Mass change time series for basin 4

GIS05_grace.dat / GIS05_grace_tudr.dat: Mass change time series for basin 5

GIS06_grace.dat / GIS06_grace_tudr.dat: Mass change time series for basin 6

GIS07_grace.dat / GIS07_grace_tudr.dat: Mass change time series for basin 7

GIS08_grace.dat / GIS08_grace_tudr.dat: Mass change time series for basin 8

The file naming relates to the product generated by DTU / TU Dresden.

The time series for the entire GIS (from DTU) is shown in **Figure 5-2**.

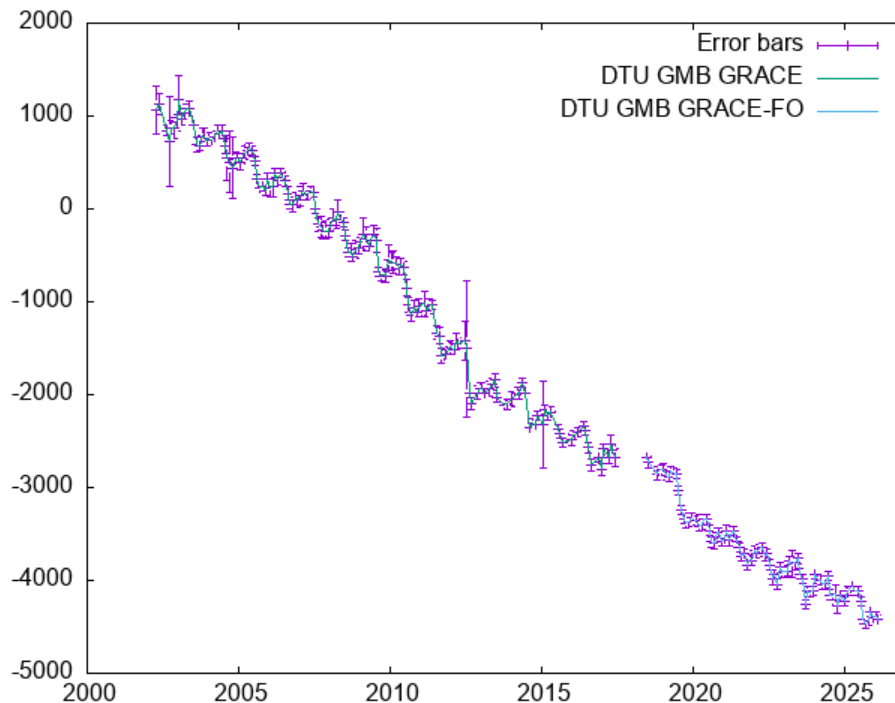


Figure 5-2: Mass change time series from the entire Greenland Ice Sheet. On the x-axis there are the time in the calendar year, on the y-axis the mass in Gigaton.

The data file will be updated at regular intervals, depending on the availability of GRACE data (some monthly epochs are currently not available, due to satellite maintenance and saving capacity on the batteries).

5.3.2 Mass trend grids

A GMB mass trend gridded product is also provided. The trends are derived for 5-year periods to be consistent with the provided SEC products. The mass trend grids are given on a ~50 km resolution grid, and are available in *one* NetCDF file spanning the period from 2002 to present-day

CCI_GMB_GIS.nc (from DTU)

CCI_GMB_GIS_TUDR.nc (from TU Dresden)

Basic metadata for the NetCDFGMB mass trend product:

Global Name	Attribute	Data Type	Description
Title		String	A descriptive title for the GMB dataset
Institution		String	Institution where the data was produced.
Method		String	Short description of underlying method (both for GDR processing and subsequent averaging and interpolation to grid)
Tracking_id		String	Universal Unique Identifier
NetCDF version		String	A text string identifying the NetCDF conventions followed.
product_version		String	The product version of this data file
date_created		String	The date on which the data was created (format yyyyymmdd)
Project		String	The scientific project that produced the data.
Latitude_min		Float	Decimal degrees north, range -90 to +90.
latitude_max		Float	Decimal degrees north, range -90 to +90.
Longitude_min		Float	Decimal degrees east, range -180 to +180.
longitude_max		Float	Decimal degrees east, range -180 to +180.
time_coverage_start		String	Time of the first measurement in the data file in the form: "yyyymm".
time_coverage_end		String	Time of the first measurement in the data file in the form: "yyyymm".
time_resolution		String	5 year trends.
grid_projection		String	Geographical coordinates relative to WGS84
Units		String	Units used (mm water equivalent per year)

Variable attributes

Variable's attributes are attached to an individual array, i.e. a grid epoch data

Variable Name	Attribute	Data Type	Description
Long_name		string	A free-text descriptive variable name.
Unit		String	Description of the physical unit.
source		string	Data source behind GMB (e.g., GRACE).

Variables in GMB mass trend product

Field name	Type	Description
Latitude	Float	Latitude of centre of grid cell (degree)
Longitude	Float	Longitude of centre of grid cell (degree)
Time	Float	Mean of time span (days after 2003-01-01)
Start_time	Float	Start of time span (days after 2003-01-01)
End_time	Float	End of time span (days after 2003-01-01)

Field name	Type	Description
GMB_trend	Float	Mass trend (mm water equivalent)

One mass trend file is shown in **Figure 5.3**.

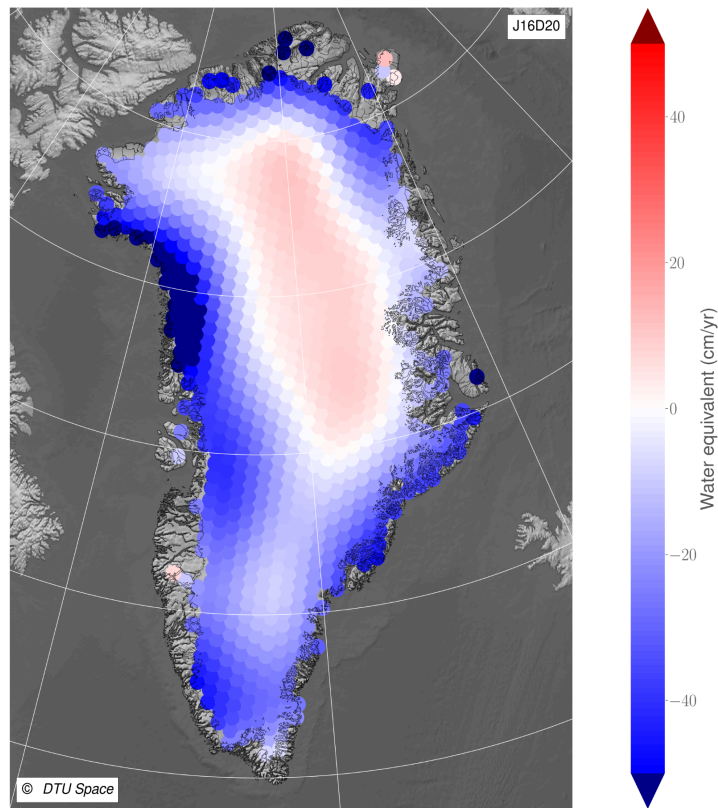


Figure 5-3: Mass trends for the 2016-2020 five-year period from GRACE.

6 The MFID product

6.1 MFID product overview

The Mass Flow rate and Ice Discharge (MFID) product utilises the cci+ data to obtain ice discharge from all outlet glaciers. By combining information about elevation changes from the SEC product with velocity changes from the IV product, the dynamical mass loss term is determined in the MFID product. The MFID is a key term in the mass budget assessment using the input-output method.

6.2 Background on product generation

The MFID product is based on the algorithm, and code from the PROMICE Solid Ice Discharge product (Mankoff et al. 2020) with minor modifications to use only freely available CCI+ IV and SEC. MFID is calculated as the flux through static flux gates located approximately 10 km upstream from the termini. The flux gates are automatically generated by first finding the fast-flowing areas of the ice sheet using a baseline velocity dataset (average winter velocity 2017-2019), then locating gates at a 10 km distance from the glacier termini. In order to calculate the total mass flux rate, the ice thickness is obtained using the subglacial bed topography from BedMachine v6 (Morlighem et al., 2022) and the Digital Elevation Model (DEM) from PRODEM (Winstrup et al. 2024).

6.3 Detailed MFID product specifications

File format

The MFID product is provided in three csv files:

1. Mass flow rate ice discharge. Units are Gt/yr.
2. Mass flow rate ice discharge uncertainty. Units are Gt/yr.
3. Coverage for each sector at each timestamp. Unitless [0 to 1].

As supplementary information, we also provide a kml file with the flux gate locations.

In the mass flow rate files total estimated discharge is always reported using gap filling of missing pixels. "Coverage" is the percentage of total basin discharge observed at any given time, thus it is 100% if no gaps have been filled.

Spatial and Temporal Resolution

The MFID is given as sums on a basin scale (defined by Zwally, 2011) with a monthly time step following the available IV products.

Global NetCDF attributes

There are no NetCDF files

7 References

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