ESA Climate Change Initiative (CCI+)

Essential Climate Variable (ECV)

Greenland_Ice_Sheet_CCI+ (GIS_cci+) Phase 2

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.Simomsen	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/corretions 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 2nd 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	All	Made revisions/corrections in all sections, according to GIS_cci+ phase 2 documents. Deleted chapters on GLL and CFL. Inserted chapters on MFID, SGL	Released to ESA 2023-05-17
	L. Søresen D. Fantin S. H. Larsen J. Wuite S.H. Larsen	Chapters 3-7	Updated the product description.	
3.1	D. Fantin C. Hvidberg	Minor edits in all sections	Updated according to review by A. M. Trofaier	

Acronyms

Acronyms	Explanation
ATBD	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CFL	Calving Front Location
CSR	Center for Space Research, University of Austin
DARD	Data Access Requirement Document
DEM	Digital Elevation Model
(D)InSAR	(Differential) Interferometric Synthetic Aperture Radar
DMI	Danish Meteorological Institute
DTU-N	DTU Microwaves and Remote Sensing Group
DTU-S	DTU Geodynamics Group
ECV	Essential Climate Variable
ENVEO	ENVironmental Earth Observation IT GmbH
EO	Earth Observation
ESA	European Space Agency
GCOS	Global Climate Observation System
GDR	Geophysical Data Record
GEUS	Geological Survey of Denmark and Greenland
GFZ	Deutsche GeoForschungsZentrum
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
IV	Ice Velocity
MEaSUREs	Making Earth System Data Records for Use in Research Environments (NASA)
MFID	Mass Flux and Ice Discharge
NBI	Niels Bohr Institute, University of Copenhagen
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
SMB	Surface Mass Balance
SOW	Statement of Work
TPROP	Technical Proposal
TUDr	Technische Universität Dresden
UL	University of Leeds
URD	User Requirement Document
OT	Offset Tracking

1 Introduction

This document is the Product Specification Document (PSD) updated for Phase 2 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 2 of the GIS_cci+ [RD1]. It is based on the GIS_cci+ Phase 2 User Requirement Document (URD) [RD2], and developed from the GIS_cci+ Phase 1 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
5) SupraGlacial Lake (SGL) - lake volume products over 79N and Zachariae catchments

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, but 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.

The PSD will be evaluated in the second iteration of Task 1 in Year 2 of the GIS_cci+ Phase 2 project.

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 describes the SGL product specifications.
- Chapter 8 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	SoW ESA-CCI-EOPS-PRGM-SOW-18-01 18	Climate Change Initiative Extension (CCI+) Phase 1 – New R&D on CCI ECVs – SoW	2018.05.31	Issue 1 Revision 6
AD3	Annex B ESA-EOP-SC-AMT-2021-53	Climate Change Initiative Extension (CCI+) Phase 2 - New R&D on CCI Essential Climate Variables -SoW (incl Annexes)	2022.06.10	Issue 1 Revision 2

Table 1.2: List of Reference Documents

No	Doc. Id	Doc. Title	Date	Issue/Revision/ Version
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-001	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

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 2 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.

For ***IV***, the provision of basic ice velocity time series provides important data on glacier dynamics changes, and – combined with ice thickness data and accumulation data in the interior – another source of the overall mass balance of the ice sheets. The scientific usefulness of such data has been demonstrated in the ESA/NASA IMBIE exercises [The Imbie team (2020); The Imbie team (2018)] for intercomparison of different EO data for estimating the overall mass balance of Greenland and Antarctica. Other important scientific and practical use of IV data relate to the production rate of icebergs of the major Greenland outlet glaciers. 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.

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. One significant additional added value is the mapping of IV along most of the ice-margin, which was first done systematically within the GIS_cci projects. Further, extending the long and dense time-series produced by ESA and ESA Third Party Mision data for the interior and of major Greenland marine outlet glaciers represents significant added value from this project, spanning periods ranging from 1991 to the present day.

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.

For **SGL**, the main added value is that it allows for detailed process studies of the effect of meltwater on ice velocity on short timescales and the evolution of mass loss on longer timescales. The combination of SGL, IV, and other ECV products as well as ancillary glaciological data provide unique opportunities for studying the effect of surface meltwater, lake drainage and ice flow. Understanding how meltwater fluctuations link to ice dynamics on shorter and longer timescales is timely and highly relevant in a warming climate with surface melting projected to increase in the future.

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 [RDx]. 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. 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].

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 2 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, 1991-2024	ERS-1, ERS-2, Envisat, CryoSat-2
IV	250 m grid	6-12 days	2014-present	Time series of coastal margin From S-1 yearly winter estimates of the entire ice sheet IV from 2014.	Sentinel-1
	250 m grid	8-32 days (depending on availability)	2021-present	Selected regions, based on repeat-pass availability of SAOCOM data	SAOCOM-1A/B
	100 m grid (50m upon request)	Seasonal	2016, 2019-present	Jakobshavn, Upernavik, Petermann, Kangerlussuaq, Hagen, Helheim, 79fjord, Zachariæ, Storstrømmen, Døcker Smith region	Sentinel-2
GMB	50 km	1 per month	2002 - present	All Greenland	GRACE/GRACE-FO
MFID	N/A	Monthly (across basins)	1991-present	Selected key ice streams	Sentinel-1A/B (and ancillary data)
SGL	10m shapefile(extent) 10m raster(geotiff) for extent and depth estimates	Specific time intervals based on cloud free S2 imagery between 1 May - 30 September	2019	79N and Zachariae catchments	Sentinel-2

<u>Comments on the selections:</u>
<u>SEC</u> – 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.
<u>IV</u> – 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.
It was planned in the first 3-year phase of the IS-CCI to do the following spatiotemporal ECV variables:

Entire Greenland ice sheet margin: Winter 1995/1996 and Summer 2008;
Selected glacier tongues: Jakobshavn, UpernavikIsbræ: time-series as dense as data allows;
Northern drainage basin (IMBIE regions 1.1-1.3).

The northern drainage basin demonstrates the ability to map the interior, slow-moving parts of the ice sheet, whereas the focus on the faster-moving margins satisfies the primary user requirements of the URD. The areas are indicated in **Figure 2-1**; for more details see also the DARD document.
<u>GMB</u> - The user required resolution in time of 1 month, and in space of 50km.

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[1]For 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 - 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.

SGL - It is an experimental product focusing on feasibility. Spatial and temporal resolution is limited by Sentinel-2 cloud-free images. The depth estimation is inherently gridded data, but the lake extent estimates are frequently published as shapefiles. In order to ease usage, we provide both shapefiles and gridded estimates.

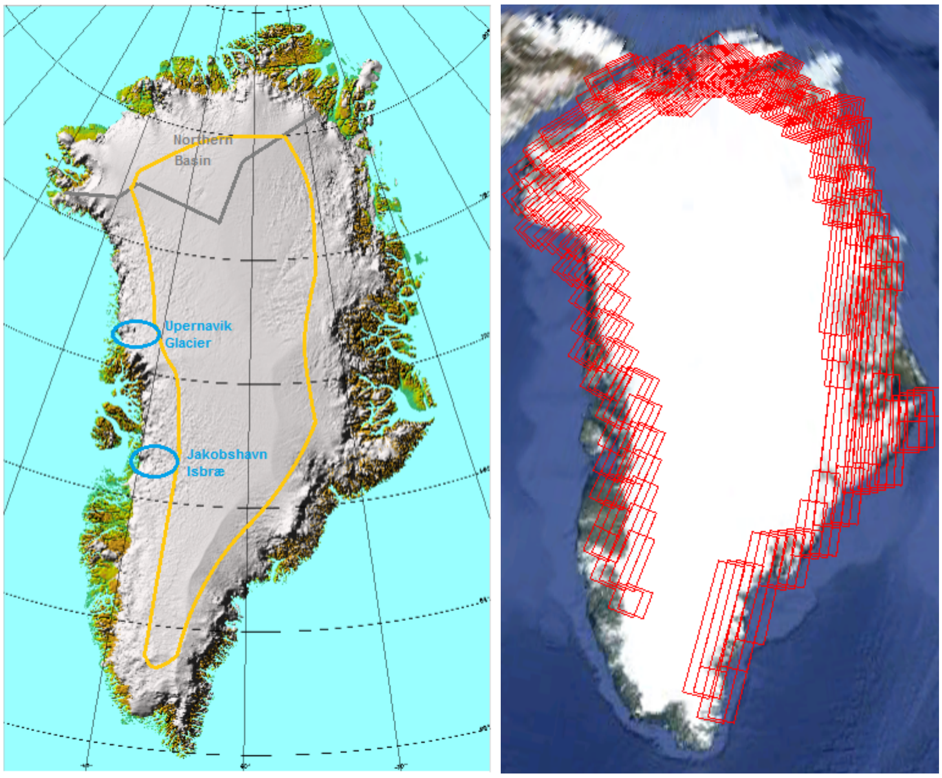

Figure 2-1: Left: Coverage of IV ECV parameter in the first 3-year phase of IS-CCI: Grey, Northern Basin (from coast to ice divide), winter 1995/96. Yellow: margin of the ice sheet (winter 1995/96 and summer 2008). Blue: Jakobshavn and Upernavik Isbræ (time series since 1991). Right: Example of actual coastal SAR coverage (ERS-2 descending, winter 1995/96).

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:

Latitude	***Scale factor, standard polar projection***	***GIS_cci projection***
82N	*1.005*	*0.975*
70N	*1.031*	*1*
60N	*1.072*	*1.040*

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.

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 REAPER)
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).

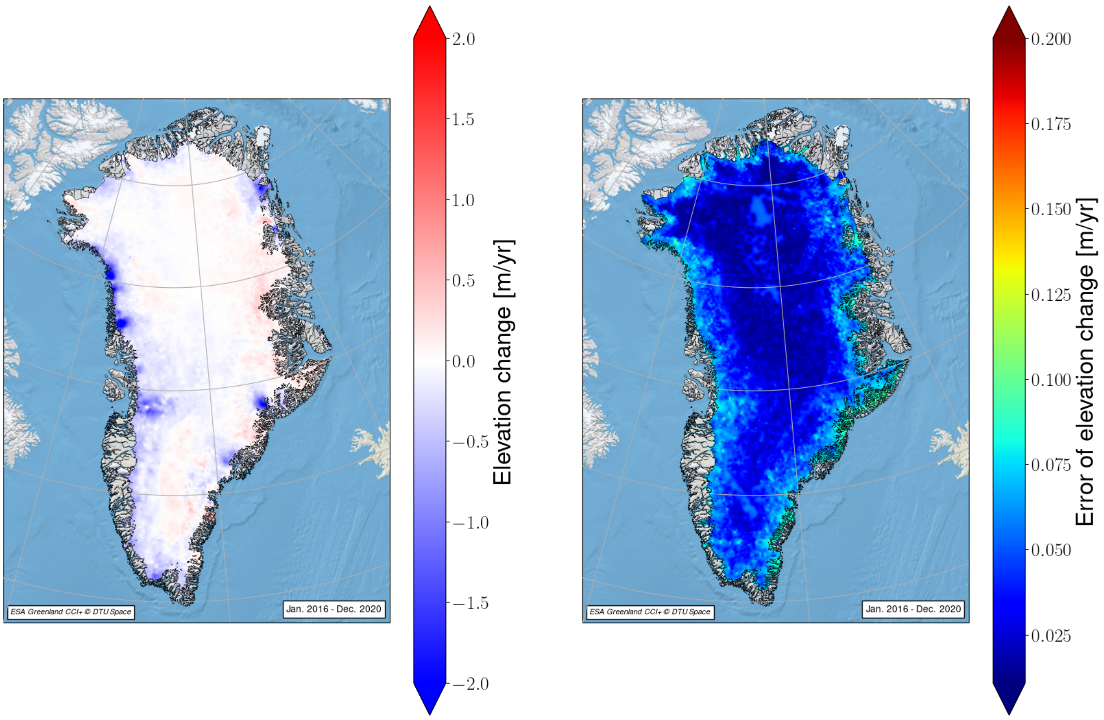

Figure 3.1: Left: SEC derived for Greenland at 5km grid from 2016-2020. Right: The error associated with the derived SEC from 2016-2020.

Global NetCDF attributes

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

Global Attribute Name	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)

Global Attribute Name	Data Type	Description
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
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.

4 The IV product

4.1 IV products overview

The SAR IV product in GIS_cci is based on a combination of several SAR techniques, namely Differential SAR Interferometry and offset tracking. The latter is also used on optical imagery (Optical IV), for epochs/areas where SAR data is not available and as a complementary and independent calculation of IV. Further details of the methods are provided in the following section and in the Algorithm Theoretical Basis Document (ATBD) [RD4].

The IV measured by space-borne SAR and optical sensors represents a mean velocity value, referred to as a temporal span ranging from a minimum value provided by the satellite repeat-cycle (between 1 to 46 days for past and current sensors) to higher ones, typically several months, required to cover areas as large as the whole GrIS or to increase measurement sensitivity.

The user community expressed a clear interest in covering large areas and providing as long as possible IV time-series [RD2]. Concerning spatial coverage and resolution, there was a general consensus that mapping of the interior should have lower priority and resolution compared to the ice margin. Concerning temporal coverage and resolution, long time series are essential to several user groups, with optimum and minimum temporal resolutions ranging from 1 month to 1 year respectively.

The current SAR and optical archive allows the user temporal resolution and temporal coverage requirements to be met on limited areas, e.g. selected glacier tongues, albeit for some data gaps. Vice versa, spatial coverage requirements can be met, coupled with a limited temporal resolution, e.g. seasonal. The IV production baseline is driven by these considerations. Also, the capability of mapping the interior is demonstrated.

Further details and plots of the spatiotemporal coverage of the production scenarios are provided in [RD4], sections 2.1.2 and 3.5.2, whereas this document focuses on the product specifications, detailed in section 4.3. Concerning this aspect, the majority of users require the IV measurements to be provided as grids of Cartesian velocity components in a stereographic projection [RD2].

This user requirement can be easily met concerning gridding, since IV measurements derived from imaging sensors are naturally gridded in the image geometry, which can be resampled to any map projection, given orbital information and an external DEM.

Concerning the measurement of velocity components, in the SAR case, the basic measurements on a given area will typically be of the form

- V_r and/or V_a measurements from the same pass (e.g. descending);
- V_r and/or V_a measurements from intersecting ascending and descending passes.

where the velocities are in the slant-range (across-track) and azimuth (along-track) directions, respectively. Cartesian velocity components, and their associated error estimates, can be generated directly from the SAR measurements when three independent velocity measurements are available. If only two are, which is typically the case for the current data archives, the Surface Parallel Flow assumption can be used [Reeh et al. (1999)].

For each of the scenarios mentioned above, the CCI IV product is therefore a set of gridded north and east (surface-parallel) SAR / Optical velocities, v_N and v_E, with associated error estimates.

4.2 Background on product generation

4.2.1 SAR IV product

The SAR IV ECV product is generated primarily from SAR offset-tracking, with InSAR used, when applicable, to increase accuracy and resolution of the measurements. This is due to the more general applicability (reduced sensitivity to coherence) and greater robustness (no phase unwrapping required) of offset-tracking techniques, as detailed in the ATBD [RD4], section 3.3. In particular, for the current archive, the latter are the only techniques, which can provide measurements over the full range of velocity magnitudes expected for the GrIS (up to 15 km/yr). It should be kept in mind that all measurement techniques provide results only in feature-rich and/or coherent areas.

The production scenarios mentioned in the previous section, and detailed in [RD4], sections 2.1.2 and 3.5.2, require mosaicking of IV measurements derived from individual pairs of data strips, i.e. consecutive acquisitions from the same ground track. In general, this requires a two-stage process.

In the first step, all the sources of East, North, and Up Cartesian velocity components are generated and re-sampled to the output grid. Each source consists of a combination of available slant-range and azimuth velocity measurements, generated by offset-based and/or phase-based methods, from which Cartesian components can be derived, if needed under the assumption of Surface Parallel Flow. For instance, a slant-range and azimuth velocity measurement derived from offset tracking applied to a data strip pair would represent a single source. However, if this strip were overlapping with a second one, acquired from a different pass, and to which offset tracking was applied, more than two sources would become available. In fact, in the region of overlap, Cartesian IV components could be derived from four independent measurements, providing a third source for IV measurement. For further processing, error estimates (standard deviation) of each Cartesian component must also be generated, based on those of the slant-range and azimuth components.

In a second processing step the contributions from each source are mosaicked, spatially and temporally, yielding, in general, a time-series of one or more gridded vN and vE maps, and associated error estimates.

Spatially, provided bias-errors can be significantly reduced by a successful baseline calibration procedure (see ATBD [RD4], section 3.3), the optimal (Maximum Likelihood) method for combining each source (Cartesian components of the velocity) is a weighted average, with weights inversely proportional to the estimated error standard deviation of each IV component, output by the first processing step. The weights will typically also need to be "feathered", i.e. adjusted in order to reduce possible spatial discontinuities arising in regions of overlap and near data borders and data voids.

Temporally, if sufficient SAOCOM data is available, one grid per month shall be generated for the area of interest. For the continuous production of ice velocity at the ice sheet margin, based on Sentinel-1, the temporal resolution shall depend on the repeat-pass period (6-12 days). For the winter scenarios, all IV sources based on imagery acquired during the winter mapping campaign shall be combined in a map.

A final remark concerns the nature of the IV measurements based on SAR data. These refer to the mean velocity of an ice-sheet volume with a vertical extent related to the penetration depth of the microwave carrier frequency in the snow/ice, typically of several meters [Reeh et al. (1999)], and a horizontal extent depending on the size of the sensor resolution cell and on the measurement technique.
Further details on the IV generation algorithms are provided in the ATBD [RD4].

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 them 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].

4.3 Detailed IV products specifications

File format

SAR IV product:
The product is provided as either NetCDF or GeoTIFF file with separate layers for the velocity components: vx, vy, vz and vv (magnitude of the horizontal components), and maps showing the valid pixel count and uncertainty (std). 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 map is provided in the North Polar Stereographic projection (EPSG: 3413, defined at https://epsg.io/3413). The horizontal velocity is provided in true metres per day, towards the easting (vx) 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. The spatial and temporal resolution is as follows:

SAOCOM SAR IV-product (selected regions):
    Spatial resolution: 100-250 m
    Temporal resolution: 8-32 days depending on availability
Sentinel-1 IV-products (margins):
    Spatial resolution: 250 m
    Temporal resolution: 6-12 days depending on availability

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, Nioghalvfjerdsfjorden 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
institution	string	Institution where the data was produced.
source	string	Original data satellite source (e.g. Envisat ASAR, ERS-1, PALSAR, Sentinel-1, Sentinel-2, mixed),
method	string	Short text describing dominant method in file
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
summary	string	A paragraph of text describing the dataset, including information on reference DEM
Date_created	string	The date on which the data was created (format yyyymmdd)
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	Date and time of the first measurement in the data file in the form: “yyyymmddThhmmss”. This time format is ISO compliant.
Time_coverage_end	string	Date and time of the last measurement in the data file
Time_averaging	string	Average time resolution of data grids, i.e. time range of data used to prepare the grid (unit: days)
Grid_projection	string	Defining parameters for the map projection used
Units	string	Units used (m/day)
NaN value	Float	Value used for no data in grid cell

Variable attributes

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

Variable Attribute Name	Data Type	Description
Long_name	string	A free-text descriptive variable name.

Variable Attribute Name	Data Type	Description
contributor	string	Contributor for ECV subset
comment	string	Miscellaneous information about the data (Identical to "comment" global attribute)
source	string	Data source behind ECV (e.g., "Envisat ASAR", etc.)
Time	string	Epoch of grid including time range of used data for gridding
SAR method	string	Method used for SAR IV processing
Optical method	string	Method used for Optical IV processing
Tie point information	string	Constraints description (ice free rock, flow model in interior)
geophysical corrections	string	Summary of corrections applied, if any (e.g. indication of matching/smoothing at overlaps)
Gridding method	string	Short summary of method of producing grid (if different from global header

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
Northing	Float	N-coordinates of centre of grid cell (m)
Easting	Float	E-coordinates of centre of grid cell (m)
Time_coverage_start	string	Date and time of the first acquisition time used for grid generation in the form: "yyyymmddThhmmss". This time format is ISO compliant.
Time_coverage_end	string	Date and time of the last acquisition time used for grid generation
V_N	Float	North velocity, m/yr
V_E	Float	East velocity, m/yr
V_N error	Float	V_N error standard deviation, m/yr
V_E error	Float	V_E error standard deviation, m/yr

5 The GMB product

5.1 GMB product overview

The Gravity Recovery and Climate Experiment (GRACE) twin satellites 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 lmax=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. 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.

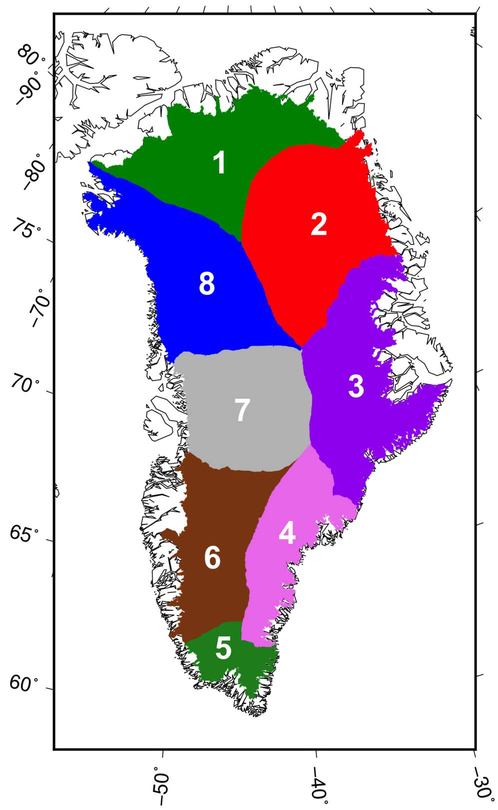

Figure 5-1: Drainage basins based on Zwally et al. (2011) in a modified way, which are used for the Basin GMB product

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**.

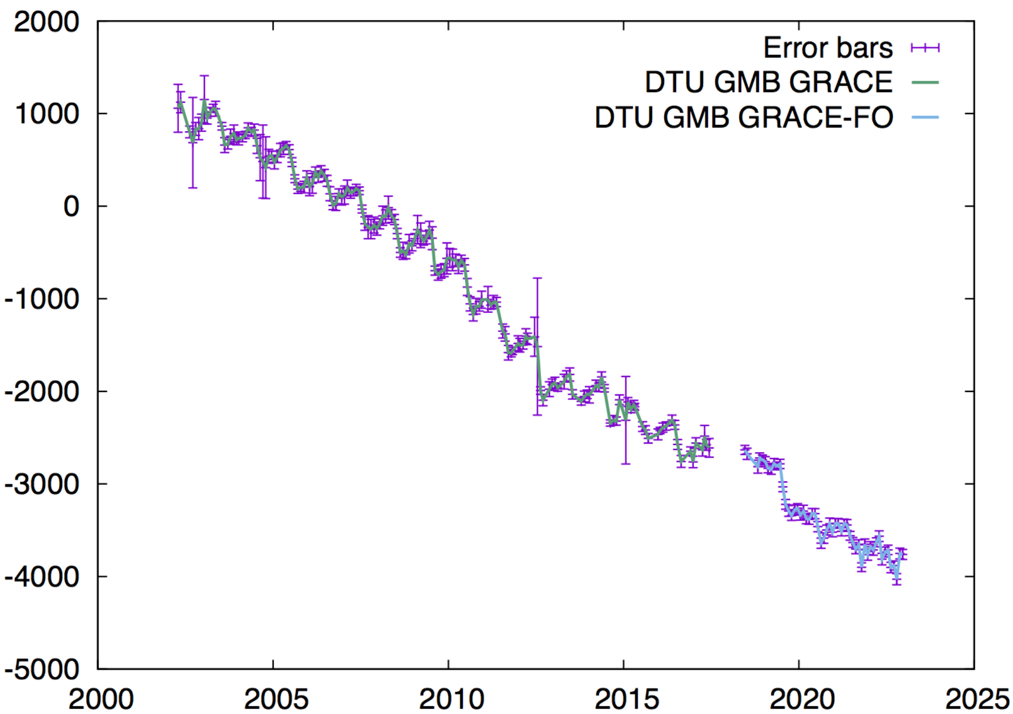

Figure 5-2: Mass change time series from the entire Greenland Ice Sheet. On the x-axis there are the time in the calendar year, on the y-axis the mass in Gigaton.

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 Attribute Name	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 yyyymmdd)
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 Attribute Name	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)

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

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

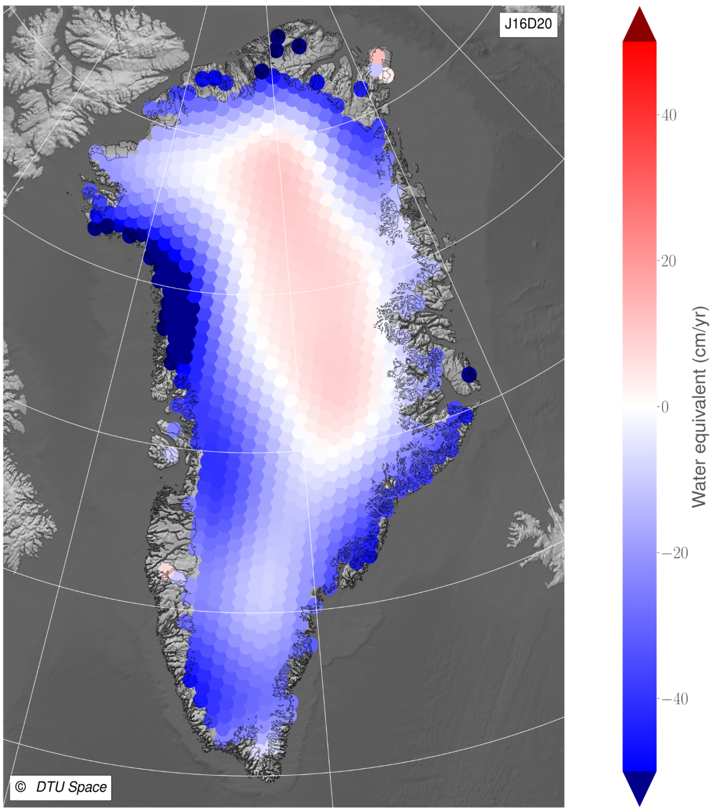

Figure 5-3: Mass trends for the 2016-2020 five-year period from GRACE.

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 key 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 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 v5 (Morlighem et al., 2022) and the Digital Elevation Model (DEM) from PRODEM (citation).

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 The SGL product

7.1 SGL product overview

Supraglacial lakes (hereafter SGLs) are temporary reservoirs of water that interact to form highly complex and dynamic hydrological networks. They form from the accumulation of meltwater on the surface of the ice sheet during the melt season (May to October). SGLs drain either laterally across the ice surface, forming streams and networks which eventually drain into the ocean, or vertically through the ice sheet via moulins. Determining the type of drainage regime is important, as moulins transport water from the surface to the subglacial bed. In regions lacking efficient drainage networks, vertical water transfer can act to lubricate the ice which increases ice flow speed. Finally, SGLs store latent heat on the surface of the ice sheet, which affects surface heat fluxes.

Approximating the measurements of IceSat-2 data from Sentinel-2 optical imagery carries the potential to provide dense spatial and temporal meltwater volume calculations. Due to the complexity of the task and the recent success of Deep Learning models for image processing, we use a joint classification and regression model in an attempt to fulfil data and knowledge gaps. Although similar research has been able to constrain SGL depth estimates from satellite imagery using IceSat-2, to the best of our knowledge, Deep Learning has not yet been exploited to predict SGL depth from Sentinel-2. In [AD1] we explore the feasibility of using Deep Learning for SGL observations in NE Greenland.

The data collection process starts by determination of the exact study area, the foreseen area is the 79 and Zacharia catchments for 2019 May - September. Possibly there will be an additional region in western Greenland. In addition, spatiotemporal train, validation and test splits are defined for the study area. Subsequently, S2 and IceSat-2 data is downloaded and labels are collected for lake extent and lake depth. For lake extent, an existing dataset from the GIS CCI Phase 1 project is used. The area is chosen because reference data for later independent validation exists for this area. Spatial generalization is a concern in machine learning models, therefore larger scale rollout could be later considered after product validation.

The product is generated from Sentinel-2 imagery, each image provides an estimate of the supraglacial lake extent and depth in clear sky conditions. The deep learning model is trained with Sentinel-2-based lake extent labels produced in GIS CCI Phase 1 and IceSat-2-based bathymetry estimations produced by DTU-S. The actual product only relies on Sentinel-2 imagery, IceSat-2 is only used for training and validation but not production. Further details of the methods are provided in the following section and in the Algorithm Theoretical Basis Document [RD4]

7.2 Background on product generation

The SGL product is generated from single Sentinel-2 L1C images, and for each image the estimates are background class, supraglacial lake, or missing data (e.g. due to clouds or if source pixels are missing). These estimates provide lake extent (discrete classes) and also for each valid extent pixel a lake depth (continuous value). Many users use lake extent-only maps, these will be published as shapefiles and gridded data, while the lake depth estimates are only generated in gridded format. The predictions from individual Sentinel-2 images are aggregated into monthly products.

7.3 Detailed SGL product specifications

NOTE: The specifications of the product are in evolution and have not been finalized yet, due to the novelty of the product and the fact that the release of the data product is foreseen only in Y2 of the project. The compliance with the product will be validated by ASIAQ during the independent validation.

File format
NetCDF files containing lake extent and depth data in grid, shapefiles containing lake extent borders.

Spatial and temporal Resolution
10m, monthly in melt season (1 May - 30 September), aiming the middle of the month (15th) generated from closest available data.

Global NetCDF attributes
This is the basic metadata for the SGL product.

Global Attribute Name	Data Type	Description
Title	String	A descriptive title for the SEC dataset
Grid_projection	String	Defining parameters for the map projection used
Lat	Float	Latitude in decimal degrees north, range -90 to +90.
Lon	Float	Longitude in decimal degrees east, range -180 to +180.
X	Float	Cartesian x-coordinate- easting
Y	Float	Cartesian y-coordinate - northing

Variables in grids

Field name	Type	Description
Land cover	int	Land cover definition (0 background, 1 supraglacial lakes, -1 missing data)
Lake depth	Float	Estimated lake depth in [m], 0 for background and missing data
Error estimation	float	Estimated error

Lake extent shapefile contains lake borders as polygons. Each polygon has the following attributes:

Attribute name	Type	Description
Date	Date	Estimated lake depth in [m], 0 for background and missing data

8 References

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