

ESA Climate Change Initiative (CCI)

Greenland Ice Sheet (GIS) Essential Climate Variable (ECV)

Product User Guide (PUG)

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Signatures page

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Change Log

| Issue | Author | Section | Reason | Status |
|-------|---|--------------|--|---------------------------------------|
| | | | For Phase 1 | |
| 0.1 | C. Aas | All | Document Creation | Released to ESA on 2014-02- 20 |
| 0.2 | D. Evensberget | All | Restructured document; added initial content for IV section. | Released to consortium on 2014-12-10. |
| 0.9 | Consortium partners | All | Added content | |
| 1.0 | D. Evensberget | All | Minor edits | Released to ESA 2015.04.14. |
| | | Figure 2.3 | Changed plot to better show ground tracks | |
| 1.1 | R. Meister, A. Kusk, | Section 2.4 | Moved mention of outliers to following section. | Released to ESA 2015.05.25 |
| | D. Evensberget | Section 3.1 | Removed contradiction in description of IV velocity vectors. | |
| | | Section 6 | Added section on data download. | |
| 1.2 | D. Evensberget | Section 3. | Replaced figures in IV section. | Released to ESA 2015.05.29 |
| | | | For Phase 2 | |
| | | | Updated for Phase 2, Year 1: | |
| | | 1.1,1.2, 1.3 | Included title and text for ref. to Phase 2 contract and SoW, and updated applicable and reference documents. | |
| 2.0 | T. Nagler | 2, 3, 4, 5 | Updated on data product descriptions. | Released to ESA 2016-06-21 |
| | | 6 | Added chapter 6 on GMB. | |
| | | / | Updated project website image and data product images | |
| | | All | Minor edits and clarifications | |
| | | | Updated for Phase 2, Year 2: | |
| | D. Fantin, A. Thorvaldsen / S[&]T | 3.2 | Added new §3.2 for Optical IV | |
| 2.1 | | 3.3 to 3.7 | Minor editorials wrt Optical IV inclusion | |
| | | 7 | Updated §7 on Project web and CCI Data Portal access to data products | |
| | J. Wuite / ENVEO | 3 | IV: update on IV products (§3.1.6 new S1 map), new §3.1.6 on Long | |
| 2.1 | | | time-series of 9 major glaciers | Released to ESA 2017-03-19 |
| | | 6 | CFL: update of product content | |
| | | Ĭ | GIVIE: change in introduction | |



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| | | | For Phase 2, Year 3 | |
|-----|--------------------------|-------|---|----------------------------|
| 2.2 | K. Khvorostovsky | 2.1.4 | Added section on Saral data processing | |
| 2.2 | A. Solgaard | 3.1.6 | Updated 3.1.6 four of the subsections in "Long time series of 9 major glaciers" and added subsection on Storstrømmen Glacier. | |
| 2.2 | J. Wuite | 5 | Updated chapter 5 on GLL | |
| 2.2 | A. Thorvaldsen/ S[&]T | 7 | Updated §7 images on Project web and images and instructions on CCI Data Portal access to products | Released to ESA 2017-11-23 |



Acronyms

| Acronym | Explanation |
|-----------|--|
| ALOS | Advanced Land Observing Satellite |
| ASAR | Advanced SAR |
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| CFL | Calving Front Location |
| DARD | Data Access Requirements Document |
| DEM | Digital Elevation Model |
| ECV | Essential Climate Variable |
| ENVISAT | ESA Environmental satellite |
| EO | Earth Observation |
| ERS | European Remote-sensing Satellite |
| ESA | European Space Agency |
| ETM+ | Enhanced Thematic Mapper plus |
| GMB | Gravimetric Mass Balance |
| GIS | Geographic Information System |
| GIS_cci | Greenland_Ice_Sheet_cci project, short form |
| GrIS | Greenland Ice Sheet |
| GLL | Grounding Line Location |
| GRACE | Gravity Recovery and Climate Experiment |
| GRACE SDS | GRACE Science Data System |
| InSAR | Interferometric SAR |
| IS | Ice Sheets |
| IV | Ice Velocity |
| LANDSAT | Land Remote Sensing Satellite |
| NASA | National Aeronautic and Space Administration |
| ODP | Open Data Portal |
| PALSAR | Phased Array type L-band Synthetic Aperture Radar |
| PG | Product Generation |
| PSD | Product Specification Document |
| PV | Product Validation |
| PVP | Product Validation Plan |
| RA | Radar Altimeter |
| RR | Round Robin |
| SEC | Surface elevation Change |
| SAR | Synthetic Aperture Radar |
| ТМ | Thematic Mapper |
| URD | User Requirement Document |



1 Introduction

1.1 Purpose and Scope

This document is updated for Phase 2 for the "Greenland_Ice_Sheet_cci" (GIS_cci) project in accordance to Contract [AD1] and Statement of Work [AD2].

This document is part of Task 3 Systems Evolution within the GIS_cci project, as part of ESA Climate Change Initiative (CCI) program.

This is the Product User Guide (PUG), describing the Greenland_Ice_Sheet_cci data products and providing information about how to download the data products.

The PUG is based on Phase 1 Product User Guide (PUG) [RD2], of the "Ice_Sheets_cci" project. The document provides information about:

- the geophysical data product content;
- the product flags and metadata;
- the data format;
- the product grid and geographic projection;
- known limitations of the product;
- available software tools for decoding and interpreting the data.

1.2 Document Structure

This document is structured as follows:

Chapter 1 is this chapter;

Chapter 2 describes the Surface Elevation Change (SEC) ECV parameter;

Chapter 3 describes the Ice Velocity (IV) ECV parameter;

Chapter 4 describes the Calving Front Location (CFL) ECV parameter;

Chapter 5 describes the Grounding Line Location (GLL) ECV parameter;

Chapter 6 describes the Gravimetric Mass Balance (GMB) ECV parameter;

Chapter 7 describes how to download the data products.

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. 4000112228/15/I-NB, and its Appendix 1 | Phase 2 of the ESA Climate Change Initiative, Greenland_Ice Sheet_cci | 2015.04.14 | - |
| AD2 | CCI-PRGM-EOPS-SW-12- 0012 Appendix 2 to contract. | Climate Change Initiative – SoW Phase 2 | 2014.06.11 | Issue 1 Revision 3 |
| AD3 | CCI-PRGM-EOPS-TN-12- 0031 | CCI System Requirements | 2013.06.13 | Version 1 |
| AD4 | CCI-PRGM-EOPS-TN-13- 0009 | Data Standards Requirements for CCI Data Producers | 2013.05.24 | Version 1.1 |



| Table 1-2: List of Reference Documen | ts |
|--------------------------------------|----|
|--------------------------------------|----|

| No | Doc. Id | Doc. Title | Date | Issue/ Revision/ Version |
|------|--|--|------------|--------------------------------|
| RD1 | ESRIN/Contract No. 4000104815/11/I-NB | Phase 1 of the ESA Climate Change Initiative, Ice_Sheets_cci | 2012.02. | |
| RD2 | ST-DTU-ESA-ISCCI-PUG-001 | Product User Guide (PUG), for Phase 1 | 2015.05.28 | 1.2 |
| RD3 | ST-DTU-ESA-GISCCI-URD-001 | User Requirement Document (URD) | | |
| RD4 | ST-DTU-ESA-GISCCI-PSD-001 | Product Specification Document (PSD) | | |
| RD5 | ST-DTU-ESA-GISCCI-DARD- 001 | Data Access Requirement Document (DARD) | | |
| RD6a | ST-DTU-ESA-GISCCI-ATBD- 001 | Algorithm Theoretical Baseline Document (ATBD) | | |
| RD6b | ST-DTU-ESA-GISCCI-ATBD- 002 | Algorithm Theoretical Baseline Document (ATBD), Round Robin Exercise | | |
| RD7 | ST-DTU-ESA-GISCCI-CECR- 001 | Comprehensive Error Characterisation Report (CECR) | | |
| RD8 | ST-DTU-ESA-GISCCI-SSD-001 | System Specification Document (SSD) | | |
| RD9 | ST-DTU-ESA-GISCCI-SVR-001 | System Verification Report (SVR) | | |
| RD10 | ST-DTU-ESA-GISCCI-PUG-001 | Product User Guide (PUG) | | |
| RD11 | ST-DTU-ESA-GISCCI-PVIR-001 | Product Validation and Inter- comparison Report (PVIR) | | |
| RD12 | ST-DTU-ESA-GISCCI-CAR-001 | Climate Assessment Report (CAR) | | |

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

The documents are available on the Greenland CCI web page http://www.esa-icesheets-greenland-cci.org/



2 Surface Elevation Change Products

This chapter describes the Surface Elevation Change ECV parameter products, based on radar altimetry measurements from ERS, EnviSat and CryoSat.

2.1 Product Geophysical Data Content

The Surface Elevation Change product contains dH/dt estimates for the Greenland Ice Sheet in 5x5 km polar stereographic grid (reference parallel 70 N, central meridian 45 W). Estimates are provided for the period 1992-2012, in 5-yearly running means. In addition, error estimates are provided. The product content varies slightly from the originally proposed data content defined e.g. in the IODD v1.2 and PSD v1.2. For instance the surface elevation relative to a reference DEM and their associated errors, as well as the geophysical correction parameters, outlined in the PSD v1.2 (*Variables in grids*, page 15) are not included in the final product. This is due to the fact that the Round Robin SEC exercise, carried out after the PSD was composed, found that a combination of repeat-/ along-track results and crossovers provides the most reliable dH/dt. This means that the geophysical corrections, which are applied in the pre-processing steps, are not part of the output.

The available product parameters are given below in Table 2-1. Please note that in addition to polar stereographic eastings and northings, the NetCDF output files also contain geographic latitude and longitude.

| Field name | Туре | Description |
|-------------------|-------|--|
| Northing | Float | N-coordinates of centre of grid cell (m) |
| Easting | Float | E-coordinates of centre of grid cell (m) |
| Grid Projection | Char | Description of the grid projection |
| Longitude | Float | Longitude of centre of grid cell (degrees) |
| Latitude | Float | Latitude of centre of grid cell (degrees) |
| Land type | Short | Description of land type, i.e. ice, ocean, ice cap, ice sheet |
| 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. |
| SEC_trend | Float | Surface elevation change long-term trend, m/yr, running 5-year mean |
| SEC_trend_error | Float | Error of SEC_trend |

Table 2-1: Output parameters for SEC data product.

In addition to the variables listed above, each NetCDF file also contains a number of global attributes, including among others the institution responsible for product creation, which method and data sets were used in the analysis, as well as the time coverage of each data set.

As well as NetCDF files, the data products and their associated errors are also provided in ASCII format. Further information on the data files is given below. Furthermore, plots of input and combined output data are made available. This means that for every five-year period, the following files can be found:

- 1. a NetCDF file (called 'SEC_*_XO.nc')
- an ASCII file containing dH/dt in geographic latitude and longitude (called `all_dhdt_*_filt.dat')
- 3. an ASCII file containing the dH/dt errors, in geographic latitude and longitude (called 'all_err_*.dat')
- 4. an ASCII file containing dH/dt in polar stereographic format (called `all_dhdt_*_filt.gri')
- 5. an ASCII file containing the dH/dt errors, in polar stereographic format (called `all_err_*.gri')



- 6. a plot of the repeat- / along-track input data (called `*dHdt_*_RT.pdf'* or `*dHdt_*_AT.pdf'*)
- 7. a plot of the crossover input data (called `dHdt_*_XO.pdf')
- 8. a plot of the combined dH/dt result (called `*Comb_RT_XO_*.pdf*' or `*Comb_AT_XO_*.pdf*')

For the version 2 of the products (updated CryoSat data) the data are given as a 5-year running mean trend, as well as new 2-year mean trends, both as NetCDF files and as GRAVSOFT grids.

The ASCII files are provided in *gravsoft* format, which is described in the following: the GRAVSOFT standard format for <u>point data</u> is very simple: line files are represented as lists of form

line_no, no_of_points

ID(1), latitude, longitude, height, data #1, data #2 ..

ID(2), latitude, longitude, height, data #1, data #2 ..

..

ID(line_no), latitude, longitude, height, data #1, data #2 ..

The simple data line format allows for easy editing of files into any applications, and may be specially suited for the ice sheet monitoring community, and general public.

The GRAVSOFT convention for <u>grid data</u> is as follows:

Data are stored row-wise from north to south, like you would read the values if they were printed in an atlas. The grid values are initiated with labels with limits and spacing of northing or latitude (f) and easting or longitude (I), and are followed by data in a free format:

 $\begin{array}{l} \phi_1 \;,\; \phi_2 \;,\; \lambda_1 \;,\; \lambda_2 \;,\; \Delta \phi,\; \Delta \lambda \\ (+ \; optional \; map \; projection \; codes: \; UTM \; zones \; or \; Polar \; Stereographic \; parameters) \\ d_{n1} \;\; d_{n2} \; \ldots \; d_{nm} \\ \ldots \\ d_{11} \;\; d_{12} \; \ldots \; \quad d_{1m} \end{array}$

Each east-west row must start on a new line. Unknown data may be signalled by "9999". The grid label defines the exact latitude and longitude of the grid cell centre points, irrespectively whether the grids point are values or average values over grid cells. The first data value in a grid file is thus the NW-corner (φ_2 , λ_1) and the last the SE-corner (φ , λ_2). Map projections are signalled with two optional integer codes, and multiple grids may be in same file (e.g., for N and E IV components).

The GRAVSOFT grid format for map projection data specifies the label in the form:

 N_1 , N_2 , E_1 , E_2 , ΔN , ΔE

iell izone

where the two last parameters signal UTM parameters or stereographic parameters (-latitude, reference longitude). (-70, -45) is the CCI default Polar Stereographic projection.

DTU Space distributes global marine altimetry ocean grid products and terrain models in this format, see e.g. <u>www.space.dtu.dk/English/Research/Scientific data and models/</u>. The data format is also supported by e.g. ESA-GUTS and a number of simple plotting and GIS programs.

2.1.1 Envisat 2002-2010 and 2010-2012 data processing

During the period 2002-2010, Envisat operated in a repeat orbit. dH/dt estimates were derived through a repeat track analysis and subsequently combined with crossovers. Data are available for the entire ice sheet. An example of ground track configurations is given below for the Jakobshavn area (Figure 2-1).

From October 2010 onwards, the Envisat orbit was changed and the inclination was not controlled any longer. Below is an example of ground tracks for that period. For the five-year mean 2007-



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2011 (only entire years are used), and along-track method is applied to the data to derive dH/dt's before merging with crossovers (Figure 2-2).



Figure 2-1: 35-day Envisat repeat tracks example Jakobshavn area

Jakobshavn non repeat tracks



Figure 2-2: Envisat drifting orbit tracks example Jakobshavn area

2.1.2 REAPER ERS-1 and ERS-2 processing

As ERS-1 operated in several different orbit configurations, a repeat track analysis is not possible. Therefore, only crossover data are available for the period 1992-1996. For the period 1996-2002, ERS-2 data were analysed using a repeat track approach and merged with crossovers. For the period 1999-2006, ERS-2 and Envisat data were combined in the following way, with the satellite spanning the longer time period being designated as the base tracks, and data from the shorter satellite being searched in the vicinity:

1999-2003 – four years ERS-2 & one year Envisat 2000-2004 – three years ERS-2 & two years Envisat 2001-2005 – two years ERS-2 & three years Envisat 2002-2006 – one year ERS-2 & four years Envisat



Figure 2-3: ERS-2 ground tracks for 1995. To make the tracks visible, only a subset of the data points are plotted.

Both ERS-1 and ERS-2 data cover the entire ice sheet, see Figure 2-3. For all variables, a fill value of 9999 is used, indicating no-data. Global attributes contain information on the sensors used, upper and lower time bounds for the entire file, the product version, SEC methods used (repeat tracks, along track, crossovers) and the date of creation. An example NetCDF header is provided in Section 2.3.

2.1.3 CryoSat data processing (v2 of the ECV products)

CryoSat data has been processed for the period 2010-2015, and are made available for the version 2 update as:

- 1) a 5-year running mean product, and
- 2) a 2-year running mean product.

The products are averaged to 5 km Polar Stereographic grid cells, analogously to the ERS/Envisat product, with a mild spatial filtering. The 2-year product is by its nature noisier than the 5-year mean.

The underlying estimations are based on a 1 km sampling grid.

2.1.4 Saral data processing

Saral with AltiKa radar altimeter on-board operated on the same repeat orbit as Envisat for the period 2013-2016. From July 2016 a new Drifting Phase began and the repetitive ground track is no more maintained.

Saral/AltiKa data has been processed for the period 2013-2017 by plane-fit method applied for Cryosat-2 data processing and crossover method, and then the results were merged into one 4-yr dH/dt product.



2.2 Product Data Format

A sample NetCDF file dump containing all grids is given below:





| Reference | : ST-DTU-ESA-GISCCI-PUG-001 | |
|-----------|-----------------------------|-------|
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| <pre>:Method = "Surface elevation changes are obtained using 1) the repeat track method and 2) the crossover method. These are subsequently merged using a collocation method and filtered to a 5km grid." ; :Tracking_id = "49140755-2c90-4644-93a4-96d7df261d27" ; :netCDF_version = "NETCDF3_CLASSIC" ; :product version = "1.0" ;</pre> |
|---|
| :Summary = "This data set is based on Envisat data whilst operating in a repeat orbit." ; |
| :date created = "Created Wed Jan 28 16:25:39 2015"; |
| :Project = "is cci" ; |
| :Latitude min = 58.8545808202139 ; |
| :Latitude max = 84.004921448222 ; |
| :Longitude min = -90. ; |
| :Longitude max = 7.59464336859143 ; |
| :time_coverage_start = "2005-01-01T00:00:002" ; |
| :time_coverage_end = "2009-12-31T23:59:59Z" ; |
| :time_resolution = "5-year running mean" ; |
| :grid_projection = "polar stereographic projection, WGS84, latitude of projection origin is 90.0N and standard parallel |
| is 70.0N"; |
| :reference_DEM = "Greenland Mapping Project (GIMP) Digital Elevation Model: Howat, I.M., A. Negrete, B.E. Smith, 2014, |
| The Greenland Ice Mapping Project (GIMP) land classification and surface elevation datasets, The Cryosphere, 8, 1509–1518, |
| doi:10.5194/tc-8-1509-2014"; |
| } |

2.3 Product Grid and Projection

The selected map projection for all the Ice Sheets CCI data products is: polar stereographic with reference latitude at 70N, reference meridian at 45W, and using the WGS84 ellipsoid.

2.4 Product Known Limitations

The main limitations presented by radar altimetric measurements of ice surfaces are the non-nadir location returns of the echo, and the penetration of the radar beam into snow and firn surfaces (see Section 2.4.1.4 of the ATBD document). Outliers in the mountainous coastal regions are unavoidable and apparent in the products.

2.5 Available Software Tools

The Ice Sheets CCI surface elevation change product is distributed in a classic NetCDF file. The layout is inspired by the CF-Metadata conventions, such that it can be readily ingested and displayed by common NetCDF display programs, and is largely self-documenting

2.6 References

FLevinsen, J., Khvorostovsky, K., Ticconi, F., Shepherd, A., Forsberg, R., Sørensen, L. S., Kleinherenbrink, M. (2013). ESA's Ice Sheets CCI: validation and inter-comparison of surface elevation changes derived from laser and radar altimetry over Jakobshavn Isbræ, Greenland – Round Robin results. *The Cryosphere Discussions*, (7), 5433-5460.



3 Ice Velocity Products

This chapter describes the Ice Velocity ECV parameter products.

3.1 Product Geophysical Data Content

The SAR IV set contains velocities components in x, y direction, and the elevation change due to the horizontal displacement which is derived from the DEM, and also normalized to meters per day. This set of 3 components allows calculating the magnitude of the horizontal velocity, and the magnitude of the surface parallel component.

The v_x and v_v contain component velocities in the x and y directions of the grid defined by the used map projection, i.e. the polar stereographic grid. These velocities are true values and not subject to the distance distortions present in a polar stereographic grid. Small holes have been filled via interpolation in some areas. The main data variables are given in Table 3-1.

NB: In version 1.0 of the user guide and the accompanying products, velocities were provided as geographic East/North velocities and not in the grid projection system. These products have since been updated to provide x/y-velocities instead. The updated products have version number 1.1. The values are provided on a 500 m by 500 m grid. The following subsections describe the IV products generated and released in this project.

| Variable name | Variable description | |
|--|--|--|
| land_ice_surface_northing_velocity | Ice velocity in true meters per day in direction of the y- component of the grid defined by the map projection [m/day] | |
| land_ice_surface_easting_velocity | Ice velocity in true meters per day in direction of the x- component of the grid defined by the map projection [m/day] | |
| land_ice_surface_vertical_velocity | Surface slope in meters per day derived from the DEM due to horizontal displacement [m/day] | |
| land_ice_surface_northing_velocity_std | Ice velocity North component estimated standard deviation [m/day] | |
| land_ice_surface_easting_velocity_std | Ice velocity East component estimated standard deviation [m/day] | |

Table 3-1: SAR IV main data variables.

3.1.1 Greenland margin winter 1995-1996 from ERS-2

The winter margin 1995-1996 product is generated from ERS-2 data. The input data and product is shown in Figure 3-1.

greenland

ice sheet





Figure 3-1: Greenland margin winter 1995-1996 from ERS-2

3.1.2 Greenland northern drainage basins 1991-1992 from ERS-1

The northern drainage basins 1991-1992 product is generated from ERS-1 data. The sparse coverage of the Northern Drainage basin is due to the fact that only data from the 3-day repeat ice phase has been used. The input data and product is shown in Figure 3-2.



Figure 3-2: Northern drainage basins 1991-1992 from ERS-1

3.1.3 Greenland margin winters 2006-2011 from PALSAR

The margin winters 2006-2011 product is generated from PALSAR data. The input data and product is shown in Figure 3-3.





Figure 3-3: PALSAR data sets and data product. Left: PROMICE data set. Centre: ALDEN data set. Right: Greenland margin winters 2006-2011 from PALSAR product

3.1.4 Upernavik long term glacier time series

The Upernavik glacier time series is produced from several sensor inputs and times as shown in Table 3-2. The input data and product is shown in Figure 3-4.

| Sensor | Period | Frequency |
|---------------|-----------------------------|------------------|
| Envisat/ASAR | 2002-2010 | 35 days (mostly) |
| ERS1 and ERS2 | 1992, 1993, 1995,1996, 2011 | Sporadic |
| ALOS/PALSAR | 2007-2010 | Three |

Table 3-2: Upernavik glacier time series input data



Figure 3-4: Upernavik glacier time series (image shows January 1992).

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3.1.5 RADARSAT-2 Early 2014 Ice sheet wide

An ice sheet wide velocity map has been produced using RADARSAT-2 data acquired from 21.1.2014 to 2.4.2014. 528 24-day SLC pairs and 136 28-day pairs were processed. The map is shown in Figure 3-5. At the margin, stable ground control points on rock were used for the calibration of velocities. In the interior, where stable ground control points were not available, low-velocity moving control points extracted from the Sentinel-1 velocity map from 2014/2015 (see Section 3.1.7) were used to calibrate the measurements.



Figure 3-5 RADARSAT-2 Greenland Ice Sheet Map from early 2014. Left: Coverage of SLC pairs. Right: Ice velocity magnitude map, based on data from 21.1.2014 to 2.4.2014.

3.1.6 Long time series of 9 major glaciers

Time series of ice velocity of 9 major glaciers: Petermann Glacier, Nioghalvfjerdsfjorden Glacier, Zachariae Isstrøm, Storstrømmen Glacier, Kangerlussuaq Glacier, Helheim Glacier, Jakobshavn Isbræ and the Upernavik Glaciers. Velocity maps have been produced from a combination of ERS-1, ERS-2, Envisat and in some cases Palsar data (Figure 3-6). The time series include data from the period 1991 to 2010 and uses available repeat times from 1 to 35 days –for coverage of the individual glaciers see further down. Velocity maps produced from image pairs with a short repeat cycle can improve the coverage of fast flowing areas, but comes at the expense of more noise. Background bedrock data in the sample plots is from *Morlighem et al*, 2014¹ and 2015².

¹ Morlighem, M., E. Rignot, J. Mouginot, H. Seroussi and E. Larour. 2014. Deeply incised submarine glacial valleys beneath the Greenland Ice Sheet, Nature Geoscience, 7:418-422. doi:10.1038/ngeo2167

² Morlighem, M., E. Rignot, J. Mouginot, H. Seroussi and E. Larour. 2015.IceBridge BedMachine Greenland, Version 2, [indicate subset used]. Boulder, Colorado USA: NASA DAAC at the National Snow and Ice Data Center.



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Figure 3-6: Input data for the ice velocity time series of the 9 major outlet glaciers in Greenland.

3.1.6.1 Hagen Glacier long term time series

Time series of ice velocity for Hagen Glacier generated using ERS-1, ERS-2 and Envisat data acquired during the period August 26 1991 to May 7 2010 (Figure 3-7). Image repeat times vary from 6 to 35 days.

| Sensors | Period | Frequency | No of Image Pairs |
|-----------------|------------------|-----------|-------------------|
| FRS-1 FRS-2 and | 26/8-1991 | | |
| Envisat | to 07/05-2010 | 6-35 days | 294 |
| | 07703 2010 | | |





Map availability and image time diff:Hagen



Figure 3-7: Left: Sample image of Hagen Glacier velocity data. Right: Velocity map availability overview.

3.1.6.2 Nioghalvfjerdsfjorden glacier and Zachariae Isstrøm long term time series

Time series of ice velocity for the area covering Nioghalvfjerdsfjorden Glacier and Zachariae Isstrøm generated using ERS-1, ERS-2 and Envisat data acquired during the period August 1 1991 to February 7 2011 (Figure 3-8). Image repeat times vary from 1 to 35 days.

| Sensors | Period | Frequency | No of Image Pairs |
|-----------------------------|----------------------------|-----------|-------------------|
| ERS-1, ERS-2 and Envisat | 1/8-1991 to 7/2-2011 | 1-35 days | 648 |



Map availability and image time diff:Zach_and_79fjord

Figure 3-8: Left: Sample image of ice velocity data for the area covering Nioghalvfjerdsfjorden Glacier and Zachariae Isstøm. **Right**: Velocity map availability overview



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3.1.6.3 Storstrømmen Glacier long term time series

Time series of ice velocity for the area covering Storstrømmen Glacier generated using ERS-1, ERS-2 and Envisat data acquired during the period October 6 1991 to March 20 2010 (Figure 3-8). Image repeat times vary from 9 to 35 days.

| Sensors | Period | Frequency | No of Image Pairs |
|-----------------------------|-----------|-----------|-------------------|
| | 6/10-1991 | | |
| ERS-1, ERS-2 and Envisat | to | 9-35 days | 69 |
| | 20/3-2010 | | |



Figure 3-9: Left: Sample image of ice velocity data for the area covering Storstrømmen Glacier. **Right**: Velocity map availability overview

3.1.6.4 Kangerlussuaq Glacier long term time series

Time series of ice velocity for Kangerlussuaq Glacier generated using ERS-1, ERS-2 and Envisat data acquired during the period January 2 1992 to December 17 2008 (Figure 3-10). Image repeat times vary from 3 to 35 days.

| Sensors | Period | Frequency | No of Image Pairs |
|-----------------------------|------------------------------|-----------|-------------------|
| ERS-1, ERS-2 and Envisat | 2/1-1992 to 17/12-2008 | 3-35 days | 62 |





Figure 3-10: Left: Sample image of Kangerlussuaq Glacier velocity data. Right: Velocity map availability overview

3.1.6.5 Helheim Glacier long term time series

Time series of ice velocity for Helheim Glacier generated using ERS-1, ERS-2 and Envisat data acquired during the period May 29 1996 to February 26 2010 (Figure 3-11). Image repeat time is 35 days.

| Sensors | Period | Frequency | No of Image Pairs |
|-----------------------------|-----------|-----------|-------------------|
| | 29/5-1996 | | |
| ERS-1, ERS-2 and Envisat | to | 35 days | 38 |
| | 26/2-2010 | | |



Figure 3-11: Left: Sample image of Helheim Glacier velocity data. Right: Velocity map availability overview

3.1.6.6 Jakobshavn Isbræ long term time series

This product consists of two time series of ice velocity for Jakobshavn Isbræ generated using ERS-1, ERS-2 and Envisat data acquired during the period January 27 1992 to September 23 2010. Image repeat times vary from 1 to 35 days.



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'Greenland_Jakobshavn_TimeSeries_2002_2010' contains the older version of the time series kept for completion and to ensure the best temporal coverage. This time series is based on Envisat data acquired between 10/11-2002 and 23/09-2010 and contains 47 maps.

'greenland_jakobshavn_timeseries_1992_2010' contains the new version of the time series based on ERS-1/2 and Envisat data acquired between 27/1-1992 and 26/02-2010 and contains 120 maps.

| Greenland_jakobsha | avn_timeseries_ | _1992_2010 |
|--------------------|-----------------|------------|
|--------------------|-----------------|------------|

| Sensors | Period | Frequency | No of Image Pairs |
|-----------------------------|------------------------------|-----------|-------------------|
| ERS-1, ERS-2 and Envisat | 27/1-1992 to 13/6-2010 | 1-35 days | 120 |



Figure 3-12: Left: Sample image of Jakobshavn Isbræ velocity data from greenland_jakobshavn_timeseries_1992_2010. **Right:** Velocity map availability overview

| Sensor | Period | Frequency | ENVISAT Tracks | No of Image pairs |
|--------------|----------------------|------------------|-------------------|----------------------|
| | | | 82 (IS2) | 5 |
| Envisat/ASAR | visat/ASAR 2002-2010 | 35 days (mostly) | 117 (IS6) | 3 |
| | | 113 (IS2) | 35 | |
| | | | 354 (IS2) | 4 |

Greenland_Jakobshavn_TimeSeries_2002_2010

Map availability and image time diff:Jakobshavn 2002-2010



3.1.6.7 Upernavik glaciers long term time series

Time series of ice velocity for the Upernavik glaciers generated using ERS-1, ERS-2, Envisat and PALSAR data acquired during the period January 2 1992 to August 22 2010 (Figure 3.12). Image repeat times vary from 1 to 35 days. This product is an update of a previous product adding 54 more maps to the time series.

| . Sensors | Period | Frequency | No of Image Pairs |
|-------------------------------------|-----------------------------|-----------|-------------------|
| ERS-1, ERS-2 and Envisat, PALSAR | 2/1-1992 to 22/8-2010 | 1-35 days | 139 |





| Reference | : ST-DTU-ESA-GISCCI-PUG-001 | |
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Map availability and image time diff:Upernavik Number of maps:139



Figure 3-13: Left: Sample image of ice velocity data for the Upernavik glaciers. Right: Velocity map availability overview

3.1.6.8 Petermann Glacier long term time series

Time series of ice velocity for Petermann Glacier generated using ERS-1, ERS-2 and Envisat data acquired during the period August 16 1991 to June 1 2010 (**Figure 3-14**). Image repeat times vary from 1 to 35 days.

| Sensors | Period | Frequency | No of Image Pairs |
|-----------------------------|-----------------------------|-----------|-------------------|
| ERS-1, ERS-2 and Envisat | 16/8-1991 to 1/6-2010 | 1-35 days | 460 |

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Figure 3-14: Left: Sample image of ice velocity data for the Petermann Glacier. Right: Velocity map availability overview

3.1.7 Sentinel-1 annual ice sheet wide velocity

Three ice sheet wide velocity products are produced from Sentinel-1 data (Table 3-3 and Figure 3-15). The latest product is derived using both Sentinel-1A and 1B data and is acquired within a period of approximately 2 months during the winter campaign 2016/2017). Along with the ice sheet velocity maps (for each component) the product also includes a valid pixel count map and an uncertainty map (based on the standard deviation) (Figure 3-16).

| Sensor | Period |
|------------------|------------------------|
| Sentinel-1A | 1.11.2014 - 1.12.2015 |
| Sentinel-1A | 23.12.2015 - 31.3.2016 |
| Sentinel-1A & 1B | 23.12.2016 - 27.2.2017 |

|--|





Figure 3-15: Sentinel-1 annual ice sheet wide ice velocity map, 2014/15, 2015/16 and 2016/17.



Figure 3-16: Pixel count and uncertainty map provided with the ice sheet velocity map for 2016/17.



3.1.8 Time series of 9 major glaciers from Sentinel-1

Ice velocities for a total of 9 major glaciers are made available from 2014 onwards. The 9 glaciers are shown in Figure 3-17.



Figure 3-17: Greenland Ice Sheet outlet glaciers with S-1 ice velocity time series.

The data are given as grid files of velocities, corresponding to the Jakobshavn and Upernavik longer time series (the velocities of the new glaciers will be extended back in time in future data releases). Files are only given in NetCDF format, and currently no error grids are made available. The time series sampling is varying from glacier to glacier depending on data availability, with some glaciers (e.g. Jakobshavn) sampled up to every 6 days (shortest repeat of Sentinel-1A & 1B). Plots are also attached of velocities along the centreline of the glaciers, as a function of distance from the actual calving front. An example is shown in Figure 3-18.



Figure 3-18: Example of outlet glacier velocity plot (Petermann Glacier). Ice Velocity along the central line (coloured dots), are illustrated graphically as a function of time in the lower figure (y-axis: m/day)

3.2 Optical Ice Velocity

3.2.1 Product Geophysical Data Content

The optical IV product contains the velocity components in x and y directions. This set of 2 components allows to calculate the magnitude of the horizontal velocity, which is also included into the product. All quantities are expressed in meters per day.

The v_x and v_y variables contain the component velocities in x and y directions of the grid defined by the used map projection, i.e. the polar stereographic grid. These velocities are true values and not subject to the distance distortions present in a polar stereographic grid. The main data variables are given in Table 3-4:

| Table 3-4: opt | tical IV main data variables | |
|----------------|------------------------------|--|
| | | |

| Variable name | Variable description |
|-------------------------------------|--|
| land_ice_surface_northing_velocity | Ice velocity in true meters per day in direction of the y- component of the grid defined by the map projection [m/day] |
| land_ice_surface_easting_velocity | Ice velocity in true meters per day in direction of the x- component of the grid defined by the map projection [m/day] |
| Land_ice_surface_velocity_magnitude | Ice velocity magnitude in true meters per day [m/day] |



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3.2.2 Time series of 10 major glaciers from Sentinel-2

Optical ice velocity time series for a total of 10 major outlet glaciers are made available for 2016. The 10 glaciers are Jakobshavn, Upernavik, Døcker Smith, Petermann, Hagen, 79Fjord, Zachariæ, Strorstrømmen, Kangerlussuaq and Helheim. Their location over Greenland Ice Sheet is visualised in Figure 3-19.



Figure 3-19: Greenland Ice Sheet outlet glaciers for which optical IV is generated

Files are only given in NetCDF format: the data are given as grid files of velocities, and currently no error grids are made available. The time series are currently limited to individual pairs of data, i.e. consecutive clouds-free acquisitions from the same ground track, and sampling is varying from glacier to glacier depending on data availability. Time series will be extended in time in future data releases. More glaciers might be added later, according to needs. An example is shown in Figure 3-20.



Figure 3-20: Upernavik glacier region time series (image shows August 2016)

3.3 Products Data Format

The Ice Sheets CCI ice velocity products are distributed in a NetCDF4 file. Figure 3-21 shows the file format.



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The IV products contain the horizontal easting and northing components, v_X and v_Y , of the components of the total velocity vector parallel to the surface. The vertical component, v_Z , which is derived from a digital elevation model and used to convert velocities from radar geometry to map projection, is also provided, but only for the SAR IV products. Furthermore, the magnitude of the horizontal velocity vector is also provided for convenience.

NB: In version 1.0 of the user guide and the accompanying products, velocities were provided as geographic East/North velocities and not in the grid projection system. These products have since been updated to provide x/y-velocities instead. The updated products have version number 1.1. The main data variables are defined on a three-dimensional grid (x, y, time), where x and y are the geographic coordinates, in the projection given by the attributes of the crs variable (following CF metadata conventions). The horizontal surface velocities are derived from measured displacements in radar geometry (range, azimuth) assuming surface parallel flow and using an external DEM.

One (x, y)-grid is supplied per time value, and the value of the time coordinate represents the midpoint time of the acquisitions used to form the given grid. For each time value, a lower and an upper bound of the time (first and last contributing acquisition time) is supplied, via the *time_bnds* variable which has dimension (*time*, 2). Thus, the velocity grid for a given time represents a weighted average velocity over the period between these bounds. Note that different parts of the grid may be generated from different sets of acquisitions, so the time and *time_bnds* variables represent the midpoint, lower and upper bound for the entire (x, y)-grid. Furthermore, the velocity measurement at each pixel is a weighted average, with weights based on the estimated standard deviation of the displacement measurements available at that pixel.

```
netcdf Greenland_Margin_ERS2_1995_1996_v1.1 {
dimensions:
    y = 5201 ;
    x = 3001 :
    time = 1 ;
    bnds = 2;
variables:
    char crs :
         crs:grid_mapping_name = "polar_stereographic";
         crs:standard parallel = 70. ;
         crs:longitude_of_prime_meridian = 0. ;
         crs:straight_vertical_longitude_from_pole = -45.;
         crs:semi_major_axis = 6378137.
         crs:inverse_flattening = 298.257223563;
         crs:latitude_of_projection_origin = 90. ;
         crs:false_easting = 0.;
         crs:false_northing = 0.;
    double y(y):
         y:units = "m";
         y:axis = "Y" ;
         y:long_name = "y coordinate of projection"
         y:standard_name = "projection_y_coordinate" ;
    double x(x);
         x:units = "m" :
         x:axis = "X" ;
         x:long_name = "x coordinate of projection" ;
         x:standard_name = "projection_x_coordinate" ;
    double time(time) :
         time:standard_name = "time" ;
time:long_name = "Midpoint time of acquisitons used" ;
         time:bounds = "time bnds"
         time:units = "days since 1990-1-1 0:0:0" ;
    double time_bnds(time, bnds) ;
         time_bnds:units = "days since 1990-1-1 0:0:0" ;
    float land_ice_surface_easting_velocity(time, y, x) ;
         land_ice_surface_easting_velocity:_FillValue = 1.e+20f ;
         land_ice_surface_easting_velocity:units = "m/day" ;
         land_ice_surface_easting_velocity:description = "easting ice velocity";
         land_ice_surface_easting_velocity:grid_mapping = "crs" ;
land_ice_surface_easting_velocity:coordinates = "time y x" ;
         land_ice_surface_easting_velocity:cell_methods = "time: mean";
         land_ice_surface_easting_velocity:missing_value = 1.e+20f ;
    float land_ice_surface_northing_velocity(time, y, x);
         land_ice_surface_northing_velocity:_FillValue = 1.e+20f ;
         land_ice_surface_northing_velocity:units = "m/day" ;
         land_ice_surface_northing_velocity:description = "northing ice velocity";
         land_ice_surface_northing_velocity:grid_mapping = "crs"
```



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```
land_ice_surface_northing_velocity:coordinates = "time y x" ;
              land_ice_surface_northing_velocity:cell_methods = "time: mean ";
      land_ice_surface_northing_velocity:missing_value = 1.e+20f;
float land_ice_surface_vertical_velocity(time, y, x);
              land_ice_surface_vertical_velocity:_FillValue = 1.e+20f ;
              land_ice_surface_vertical_velocity:units = "m/day" ;
              land_ice_surface_vertical_velocity:description = "vertical ice velocity" ;
              land_ice_surface_vertical_velocity:grid_mapping = "crs" ;
land_ice_surface_vertical_velocity:coordinates = "time y x"
              land_ice_surface_vertical_velocity:cell_methods = "time: mean ";
land_ice_surface_vertical_velocity:missing_value = 1.e+20f;
      float land_ice_surface_velocity_magnitude(ime, y, x) ;
land_ice_surface_velocity_magnitude:_FillValue = 1.e+20f ;
              land_ice_surface_velocity_magnitude:units = "m/day" ;
land_ice_surface_velocity_magnitude:description = "magnitude of horizontal ice velocity" ;
             land_ice_surface_velocity_magnitude:grid_mapping = "crs";
land_ice_surface_velocity_magnitude:coordinates = "time y x";
land_ice_surface_velocity_magnitude:cell_methods = "time: meanns)";
land_ice_surface_velocity_magnitude:missing_value = 1.e+20f;
      float land_ice_surface_easting_velocity_std(time, y, x) ;
              land_ice_surface_easting_velocity_std:_FillValue = 1.e+20f ;
              land_ice_surface_easting_velocity_std:units = "m/day";
land_ice_surface_easting_velocity_std:description = "easting ice velocity error estimate ";
              land_ice_surface_easting_velocity_std:grid_mapping = "crs" ;
land_ice_surface_easting_velocity_std:coordinates = "time y x" ;
              land_ice_surface_easting_velocity_std:cell_methods = "time: mean" ;
land_ice_surface_easting_velocity_std:missing_value = 1.e+20f ;
       float land_ice_surface_northing_velocity_std(time, y, x);
              land_ice_surface_northing_velocity_std:_FillValue = 1.e+20f ;
              land_ice_surface_northing_velocity_std:units = "m/day";
land_ice_surface_northing_velocity_std:description = "northing ice velocity error estimate";
              land_ice_surface_northing_velocity_std:grid_mapping = "crs" ;
land_ice_surface_northing_velocity_std:coordinates = "time y x" ;
land_ice_surface_northing_velocity_std:cell_methods = "time: mean" ;
              land_ice_surface_northing_velocity_std:missing_value = 1.e+20f;
      float land_ice_surface_velocity_magnitude_std(time, y, x) ;
              land_ice_surface_velocity_magnitude_std:_FillValue = 1.e+20f ;
              land_ice_surface_velocity_magnitude_std:units = "m/day";
land_ice_surface_velocity_magnitude_std:description = "horizontal ice velocity error magnitude estimate";
              land_ice_surface_velocity_magnitude_std:grid_mapping = "crs";
land_ice_surface_velocity_magnitude_std:coordinates = "time y x"
land_ice_surface_velocity_magnitude_std:cell_methods = "time: "
              land_ice_surface_velocity_magnitude_std:missing_value = 1.e+20f;
// global attributes:
             iproduct_version = "1.1";

:date_created = "2016-06-14";

:title = "Greenland_Margin_ERS2_1995_1996";

:institution = "DTU Space - Microwaves and Remote Sensing";
              :summary = "Winter 1995-1996 velocity map of Greenland Icesheet Margin based on offset-tracking of ERS2 35-day
repeat acquisitions'
              :project = "ESA Greenland Icesheet CCI"
             :tracking_id = "fdfb202d-af25-4957-a60a-dd4310fe6e66";
:time_coverage_start = "1995-09-03";
:time_coverage_end = "1996-03-29";
:sensors_used = "ERS-2";
              :methods_used = "Offset-tracking";
              :calibration_method = "Control points on ice-free rock" ;
:velocity_projection_method = "Surface Parallel Flow" ;
              :Conventions = "CF-1.5" ;
```

Figure 3-21: NetCDF file format used in IV products.

3.4 Products Grid and Projection

The selected map projection for all the Ice Sheets CCI data products is: polar stereographic with reference latitude at 70N, a reference meridian at 45W, and using the ellipsoid WGS84 [PSD].

3.5 Products Flags and Metadata

For all variables, a Fill value, indicating missing data, of *3.4028235e+38* is used. Global attributes contain information on the sensors used, upper and lower time bounds for the entire file, the product version, IV methods used (offset-tracking and/or interferometry) and the date of creation. The header of an example file is given in Figure 3-21.



3.6 Products Known Limitations

For product known limitations we refer to the Algorithm Theoretical Baseline Document [ATBD].

3.7 Available Software Tools

The Ice Sheets CCI ice velocity products are distributed in a NetCDF4 file. The layout is inspired by the CF-Metadata conventions, such that it can be readily ingested and displayed by common NetCDF display programs, and is largely self-documenting.

3.8 References

Auxiliary data used in the generation of the Greenland Ice sheet ice velocity products are the Greenland Ice Mapping Project (GIMP) digital elevation model [1], and a land/sea/ice mask from the Geological Survey of Denmark and Greenland [2]

- Howat, I.M., A. Negrete, B.E. Smith, 2014, The Greenland Ice Mapping Project (GIMP) land classification and surface elevation datasets, The Cryosphere, 8, 1509-1518, doi:10.5194/tc-8-1509-2014
- [2] Citterio, M., Ahlstrøm, A.P., 2013. Brief communication "The aerophotogrammetric map of Greenland ice masses". The Cryosphere 7, 445–449, doi:10.5194/tc-7-445-2013



4 Calving Front Location Products

This chapter describes the Calving Front Location (CFL) products.

4.1 Product Geophysical Data Content

The CFL product is a collection of annotated vector files delineating the calving front locations of 28 key outlet glaciers (Figure 4-1) at various intervals in time. The format is standard ESRI line shapefile in latitude and longitude (WGS84) projection. The main attributes are shown in Section 4.3.



Figure 4-1: 28 outlet glaciers of Greenland for which CFLs are generated, for 6 of them the CFL is generated seasonally. Eleven of the selected glaciers (Jakobshavn, Upernavik, Kangerlussuaq, Kangiata Nunaata Sermia (KNS), Hagen, Helheim, Inngia, Kangilleq, Perlerfiup Sermia, Sermeq Avannarleq, Spaltegletsjer) are sampled quarterly, the remaining are sampled yearly.



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Figure 4-2: Dates of calving front location (status: 2017/09/19).

4.1.1 Annual CFLs from SAR and optical data

Annual Calving Front Location delineations have been generated from ERS and ENVISAT SAR data and Landsat 5/7/8 optical imagery for 22 of the 28 main outlet glaciers of the Greenland Ice Sheet, see Figure 4-1. The dates of derived calving fronts are shown in Figure 4-2. Figure 4-3 and Figure 4-4 show examples of CFL delineation for 79 Fjord Glacier and Kangigdleg respectively.



Figure 4-3: Calving front of 79 Fjord Glacier



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4.1.2 Seasonal CFLs for selected key glaciers

For the Upernavik, Sermaq Avannarleq, Perdlerfiup Sermia, Kangigdleq, Jakobshavn, and Ingia glaciers (see Figure 4-1) the aim was to extract CFLs multiple times per year in order to generate a time series of seasonal CFLs for these glaciers (see Figure 4-2).



Figure 4-4: Kangigdleg annual delineation

4.2 Product Flags and Metadata

At some glacier fronts brash ice and icebergs pile up in front of the main calving front. The parameter is recorded in the corresponding metadata ("pro_mat"= Material in front of the terminus: open water (OW), rock (RO), ice melange (IM), sea ice (SI)). Details on the metadata are given in Section 4.3.

4.3 Product Data Format

The digitized calving front is stored as series of latitude longitude vertices stored as vector line in standard GIS format. Additionally, metadata information on the sensor and processing steps are stored in the corresponding attribute table (Table 4-1).

CFL files are stored as *shapefiles*. This ensures a useful consistency with the glaciers CCI project, which also maps outlines of isolated Greenland glaciers.

The CFL product includes shapefiles, which contain the following information according to the GLIMS (Global Land Ice Measurements from Space) standard:

- cfl: processing information
- glaciers: positions, names and unique IDs of analysed glaciers

Table 4-1 gives the CFL product structure, which has been slightly updated to the specifications given in the PSD.



| Shapefile | Attribute | Format | Manda- tory | Attribute description |
|-----------|------------|---------------|----------------|--|
| Cfl | RC_ID | int | YES | Identification number of the Processing Agency |
| | analy_time | timestamp | YES | Time analysis was done |
| | data_src | text | YES | Description of data source |
| | proc_desc | text | YES | Description of processing: e.g. Manual, semi- automatic |
| | 3d_desc | text | YES | Description of how 3-D information was derived; e.g. DEM and Software + Software Version used for Geocoding |
| | inst_name | varchar(80) | YES | Instrument name (e.g. ETM+, ASTER) |
| | orig_id | int | YES | Original ID of image |
| | acq_time | timestamp | YES | Time of image acquisition, in 'YYYY-MM-DD' or 'YYYY-MM-DD hh:mm:ss' format |
| | imgctrlon | numeric(11,4) | YES | Longitude of image centre, in decimal degrees |
| | imgctrlat | numeric(11,4) | YES | Latitude of image centre, in decimal degrees |
| | category | varchar(32) | YES | Category of analysed line |
| | ID | varchar(20) | YES | Unique glacier ID in the form (TBD) GnnnnnEmmmmm[N S] |
| | type | varchar(30) | YES | "m" (measured) or "a" (arbitrary) |
| | loc_unc_x | numeric(11,4) | YES | Local (within-image) location uncertainty, in meters in general 1 pixel size |
| | loc_unc_y | numeric(11,4) | YES | Local (within-image) location uncertainty, in meters in general 1 pixel size |
| | glob_unc_x | numeric(11,4) | YES | Global (geographic) location uncertainty, in meters |
| | glob_unc_y | numeric(11,4) | YES | Global (geographic) location uncertainty, in meters |
| | label | char(3) | YES | Where segment is located (trm: terminus) |
| | orthocorre | char(1) | YES | Orthocorrected: yes (y), no (n) |
| | pro_mat | char(3) | NO | Material in front of the terminus: open water (OW), rock (RO), ice melange (IM), sea ice (SI), not detectable (ND) |

| glaciers | ID | varchar(20) | YES | Unique glacier ID in the form (TBD) GnnnnnEmmmmm[N S] |
|----------|------------|-------------|-----|--|
| | name | varchar(40) | NO | Name of glacier, if one exists |
| | prim_class | smallint | NO | Classification of glaciers, currently 10 valids from WGI |
| | front_char | smallint | NO | Enumerated field, 6 valids from WGI |
| | parent_id | varchar(20) | NO | Reference for parent glacier ID |

The shapefile glaciers.shp contains the positions and names of all analysed glaciers.

The session, segments and images shapefiles are named according to the following scheme:

{shapefile_name}_{glacier_name}_{date}_{time}.shp

For example: The segments shapefile of Helheim glacier which contains the CFL derived from analysis of an image with acquisition time 13:57:49 on the 20^{th} of November 1995 is named segments_Helheim_19951120_135749.shp.

4.4 Product Grid and Projection

For CFL the primary product is an ESRI shapefile in latitude and longitude, WGS84 projection. The main attributes are shown below. The basic data are vector line files (not polygons).

4.5 Product Known Limitations

Manual delineation as well as any automatic or semi-automatic method works well when the calving front can be clearly discriminated against open (calm) water due to different reflectivity,



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texture and shape in SAR and optical imagery. The identification of the calving front benefits from a better spatial resolution; however, the presence of the ice melange in front of the calving cliff can impede the detection of the frontal position. Furthermore, the ice melange can cause ambiguities in the interpretation at any spatial scale. For product known limitations we refer to the Algorithm Theoretical Baseline Document [ATBD].

4.6 Available Software Tools

The CFL product is distributed as ESRI shapefiles, which is a standard format for vector data ,and readable by almost all open source (e.g qgis: <u>www.qgis.org</u>) or commercial GIS (ARC-Info, ARC View, etc.) systems or image processing systems (e.g. PCI Geomatics). The outline of the shapefiles and metadata information follows GLIMS (see PSD). The shapefiles contain metadata information on the SAR data used for production.



5 Grounding Line Location Products

This chapter describes the Grounding Line Location ECV parameter products.

5.1 Product Geophysical Data Content

For generating GLLs (or sea and land ward limit of the tidal deformation zone) 5 glaciers were selected (Figure 5-1).



Figure 5-1: Glaciers selected for delineation of the tidal flexure zone from SAR images.

5.1.1 Grounding line from ERS SAR

Grounding line products for the 5 glaciers were generated from ERS SAR Tandem and 3 days data sets acquired in 1996/96 (Table 5-1).

5.1.2 Grounding line from Sentinel-1 IW data

Additionally, we generated groundling line for the 5 glaciers from Sentinel-1 data acquired for selected dates in 2015 and 2017 (see Table 5-1 for a complete overview). Figure 5-2 shows an example for Petermann Glacier derived from data acquired on 2 October 2015, 14 October 2015, and 26 October 2015.

| 79Fjord Glacier | 19950828 |
|--------------------|----------|
| 79Fjord Glacier | 20170305 |
| Hagen Brae | 19960316 |
| Hagen Brae | 20170316 |
| Petermann Gletsjer | 19951028 |
| Petermann Gletsjer | 20151014 |
| Petermann Gletsjer | 20170106 |
| Petermann Gletsjer | 20170203 |
| Petermann Gletsjer | 20170209 |

Table 5-1: GLL products (status Sept 2017)



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| Petermann Gletsjer | 20170211 |
|--------------------|----------|
| Ryder Gletsjer | 19960327 |
| Ryder Gletsjer | 19960418 |
| Ryder Gletsjer | 20170105 |
| Ryder Gletsjer | 20170106 |
| Zachariae Isstrom | 19950828 |



Figure 5-2: Petermann Grounding lines from 1995 (ERS) and 2015 (Sentinel-1).

5.2 Product Flags and Metadata

The product specification and metadata definition is given in the PSD. A description of the attributes is given in Section 5.3.

5.3 Product Data Format

The GLL product includes four shapefiles following the GLIMS standard (Table 5-2):

- session: processing information
- glaciers: positions, names and unique IDs of analysed glaciers
- segments: GLL vector lines
- images: information on the image file used for GLL analysis

Table 5-2 gives the GLL product structure, which has been slightly updated to the specifications given in the PSD.

| Shapefile | Attribute | Format | Mandatory | Attribute description |
|-----------|------------|---|-----------|--|
| session | RC_ID | int | YES | Identification number of the Processing Agency |
| | analy_time | naly_time timestamp YES Time analysis v | | Time analysis was done |
| | data_src | text | YES | Description of data source |
| | proc_desc | text | YES | Description of processing |
| | 3d_desc | text | YES | Description of how 3-D information was derived |
| | | | | |

Table 5-2: GLL product structure



| Shapefile | Attribute | Format | Mandatory | Attribute description |
|-----------|------------|---------------|--|--|
| glaciers | ID | varchar(20) | YES | Unique glacier ID (TBD) GnnnnnEmmmmm[N S] |
| | name | varchar(40) | NO | Name of glacier, if one exists |
| | prim_class | smallint | NO | Classification of glaciers, currently 10 valids from WGI |
| | front_char | smallint | NO | Enumerated Field, 6 valid from WGI |
| | | | | |
| segments | category | varchar(32) | YES | Category of analysed line |
| | ID | varchar(20) | YES | Unique glacier ID (TBD) GnnnnnnEmmmmm[N S] |
| | type | char(1) | YES | measured (m) or arbitrary (a) |
| | loc_unc_x | numeric(11,4) | YES | Local (within-image) location uncertainty, in meters in general 1 pixel size |
| | loc_unc_y | numeric(11,4) | YES | Local (within-image) location uncertainty, in meters in general 1 pixel size |
| | glob_unc_x | numeric(11,4) | YES | Global (geographic) location uncertainty, in meters |
| | glob_unc_y | numeric(11,4) | YES | Global (geographic) location uncertainty, in meters |
| | | | | |
| images | inst_name | varchar(80) | YES | Instrument name |
| | orig_id | text | YES | Name of image file used for GLL analysis |
| | acq_time | timestamp | YES | Time of image acquisition, in 'YYYY-MM-DD' |
| | imgctrlon | numeric(11,4) | ic(11,4) YES Longitude of image centre, in decimal degrees | |
| | imgctrlat | numeric(11,4) | YES | Latitude of image centre, in decimal degrees |

The shapefile glaciers.shp contains the positions and names of all analysed glaciers.

The session shapefiles are named according to the following scheme:

```
{shapefile_name}_{glacier_name}.shp
```

The segments and images shapefiles are named according to the following scheme:

```
{shapefile_name}_{glacier_name}_{date}.shp
```

For example: The segments shapefile of Petermann glacier which contains the GLL derived from analysis of an image from 1995-10-28 is named segments_Petermann_19951028.shp.

5.4 Product Grid and Projection

The product is given as vector data in shapefile format. The coordinates are specified in the polarstereographic map projection. Projection type and related projection parameters are stored in the shapefiles.

5.5 Product Known Limitations

SAR interferometry has been applied to detect and delineate grounding lines (sea and land ward limit of tidal deformation zone). The method is based on double differencing of interferometric pairs acquired during different tidal conditions in order to map the sea and land ward limit of the tidal deformation zone.

The generation of grounding lines requires suitable repeat pass SAR image pairs with sufficient coherence to form 2 independent interferograms acquired at different tidal conditions. Due to temporal decorrelation SAR data acquired over multi-days periods (e,g. 35 days for ERS and ENVISAT) show too low coherence and do not allow to form fringes for mapping the tidal deformation zone. In the project all available ERS-1 TANDEM (1 day repeat cycle) and ERS ice phase (3 days repeat cycle) have been processed for the selected outlet glaciers (see ATBD).



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With the launch of Sentinel-1 in April 2014 a new SAR data set became available. Initially, due to the repeat interval of 12 days, coherence was low over fast moving outlet glaciers, complicating the formation of interferograms suitable for GLL delineation. The launch of Sentinel-1B, in April 2016, has reduced the repeat pass period to 6 days providing significant improvements.

5.6 Available Software Tools

The GLL product is distributed as ESRI shapefiles, which is a standard format for storing vector data. Shapefiles are supported by almost all open source (e.g. QGIS: <u>www.qgis.or</u>) or commercial GIS (ARC-Info, ARC View, etc.) systems or image processing systems (e.g. PCI Geomatica). The shapefiles contain metadata information and information on the SAR data used for production.



6 Gravimetric Mass Balance (GMB) Products

This chapter describes the Gravimetric Mass Balance (GMB) ECV parameter products. Two products are provided for GMB: mass change time series (for GIS and individual basins) and mass trend grids for 5-year periods. These products are independently generated by DTU and TU Dresden. For products by TU Dresden, the filenames are extended by the string "_tudr". The products are described in detail in the PSD v 2.3 and the algorithms and methods in the ATBD.

6.1 Product Geophysical Data Content

6.1.1 Mass change time series

The mass change time series contains the mass change (w.r.t. a chosen reference month) for all of GIS and for each individual drainage basin (see basin definition in the ATBD).

For each month (defined by decimal year) a mass change in Gt and its associated error (also in Gt) are provided.

6.1.2 Mass trend grids

For five-year periods grids of the trend in the derived GMB is also provided. This is given in units of mm water equivalent per year.

6.2 Product Flags and Metadata

The mass trend grids are collected in one NetCDF file (CCI_GMB_GIS.nc) which contains this meta data:

| 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) |

6.3 Product Data Format

The mass change time series (GISxx_grace.dat, where xx indicated the basin number with 00 being entire Greenland) are provided in a simple ASCII format with the content: [time, mass change, error]. Figure 6-1 shows an example of total Greenland mass loss time series.



The mass trend grids are collected in one NetCDF file which contains these variable attributes:

Variable attributes

Variable 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 | Туре | 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) |
| GMB_trend | Float | Mass trend (mm water equivalent) |

6.4 Product Grid and Projection

For the mass trend grids, the location of each grid point is provided in geographical coordinates (latitude, longitude) relative to WGS84.



Figure 6-1: Example of total Greenland mass loss time series (basin 00 = all)



7 How to Obtain the Data Products

The data products are accessed as follows;

- Via project web
- Via CCI Data Portal

7.1 Project Web access to data products

The Greenland_Ice_Sheet_cci data products may be downloaded from our project web page at <u>http://esa-icesheets-greenland-cci.org/</u> as shown in Figure 7-1. This is also where project news and documentation is released.

Click on one of the 5 images under **Essential Climate Variables**, this will bring you to a page entitled e.g. 'Surface Elevation Change'. At the bottom of that page click the link e.g. '<u>Click here to</u> browse and download Surface Elevation Change products', and you will be brought to the listing of the relevant products on <u>http://products.esa-icesheets-cci.org/</u>.

Alternatively you may reach the same product listing by going directly to the products page <u>http://products.esa-icesheets-cci.org/</u>, and clicking the <u>Product Download</u> link below the desired product type.



Figure 7-1: Greenland_Ice_Sheet_cci project home page.



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| | SEC | Greenland SEC grids from ERS1, ERS2, and ENVISAT. 5-yr means for 1992-2014. | 77.0 MB | 2016-06-27 | 5 | | Institute | |
| | show of | der products | | | | NIRRS | SCIDA | \sim |

Figure 7-2: Table listing of available SEC data products.



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7.1.1 Downloading data

You arrive at the product details and download page by clicking on a link in the **Description** column in the product listing (Figure 7-2). There, click on the **Product file** link and the download will start. However, the first time you do this a registration dialog will open (Figure 7-3), where you fill in your name and affiliation. Both fields must contain at least 3 characters, and no non-characters other than '.' and '-'. Then click the 'Register' button and you will be allowed to continue with the download. All product files are in zip format.

A quicklook image can be seen under 'Preview image', a brief description of the product is provided under 'Description', and further details can be found under 'Comments' on this page (Figure 7-3).



Figure 7-3: The product details and download page with the registration dialog open.

7.1.2 Return to the downloads table

To go back to the product listing page (Figure 7-2), click on 'Home', then on 'Product Download'.

7.1.3 Log out

To make the web browser forget your registered name and affiliation (Figure 7-3) click the 'Leave' link in the top right corner of the page, which appears after registration. Then the registration dialog will reappear the next time you attempt to download a product.



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7.2 CCI Data Portal access to data products

ESA collects data products published by all CCI projects on a central, common website, the CCI Open Data Portal (ODP), URL: <u>http://cci.esa.int/data</u> (Figure 7-4).



Figure 7-4: The CCI Open Data Portal.

The ODP is updated at irregular intervals the products we publish on http://products.esa-icesheets-cci.org/. Under CCI Dashboard you have access to products published by all of ESA's CCI projects (Figure 7-5), URL: http://cci.esa.int/sites/default/dashboard/index.html#/. Selecting IS Greenland will show the (currently 23) available GIS_cci products (Figure 7-6). Selecting a product and then clicking the link "Dataset" on the right-hand side will open the corresponding product record (Figure 7-7) in the CEDA Data Catalogue, hosted by the Centre for Environmental Data Analysis (UK). The "GET DATA" button on the product record will show the list of product files available for download (Figure 7-8).





Figure 7-5: List of CCI projects on the CCI Dashboard of the CCI Open Data Portal showing the temporal coverage of each project.



Figure 7-6: Display of GIS_cci product names and temporal coverage on the CCI Dashboard. Details for the selected product can be seen on the right.



Figure 7-7: Product dataset record for one of GIS_cci's products: "Greenland Surface Elevation Change 1992-2014, v1.2" in the CEDA Data Catalogue.

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Figure 7-8 Files in one of GIS_cci's products available for download from the CEDA Data Catalogue.



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