ESA Climate Change Initiative (CCI+)
Essential Climate Variable (ECV)
Greenland_Ice_Sheet_cci+ (GIS_cci+)

Product User Guide (PUG) for CCI+ Phase 1

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Change Log

Issue	Author	Affected Section	Change	Status
0.5	S&T	All	Document Creation	
0.6	ENVEO	All	Template	
0.9	All	All	First consolidated draft	
1.0	All	All	First version	
2.0	ENVEO, S&T	Ch 3, Ch 4, Ch 8	Version 2 update, CFL added	

Acronyms and Abbreviations

Acronyms	Explanation
ATBD	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CFL	Calving Front Location
CS2	CryoSat-2
CSR	Center for Space Research, University of Austin
DEM	Digital Elevation Model
DInSAR	Differential Interferometric Synthetic Aperture Radar
DMI	Danish Meteorological Institute
DTU-N	DTU Microwaves and Remote Sensing Group
DTU-S	DTU Geodynamics Group
E3UB	End-to-End ECV Uncertainty Budget
ECV	Essential Climate Variable
ENU	East North Up
ENVEO	ENVironmental Earth Observation GmbH
EO	Earth Observation
ESA	European Space Agency
GCOS	Global Climate Observation System
GCP	Ground Control Point
GEUS	Geological Survey of Denmark and Greenland
GFZ	Deutsche GeoForschungsZentrum
GIA	Glacial Isostatic Adjustment
GIS	Greenland Ice Sheet
GLL	Grounding Line Location
GMB	Gravimetry Mass Balance
GRACE(-FO)	The Gravity Recovery and Climate Experiment (Follow On)
IMBIE	Ice Sheet Mass Balance Inter-Comparison Exercise
InSAR	Interferometric Synthetic Aperture Radar
IPP	Interferometric Post-Processing
IV	Ice Velocity
JPL	NASA Jet Propulsion Laboratory
MAI	Multiple Aperture Interferometry
MEaSUREs	Making Earth System Data Records for Use in Research
MFID	Mass Flow Rate and Ice Discharge
NBI	Niels Bohr Institute, University of Copenhagen
NEGIS	North East Greenland Ice Stream
PROMICE	Danish Program for Monitoring of the Greenland Ice Sheet
RA	Radar Altimetry
RMS	Root Mean Square
S&T	Science and Technology AS

S2	Sentinel-2
SAR	Synthetic Aperture Radar
SEC	Surface Elevation Change
SLR	Satellite Laser Ranging
SMB	Surface Mass Balance
SOW	Statement of Work
TEC	Total Electron Content
TOA	Top of Atmosphere
TPROP	Technical Proposal
TUDr	Technische Universität Dresden
UL	University of Leeds
URD	User Requirement Document

1 Introduction

1.1 Purpose and Scope

This document contains the Product User Guide (PUG) for the Greenland_Ice_Sheet_cci (GIS_cci) project for CCI+ Phase 1, in accordance with contract and SoW [AD1 and AD2]. The PUG provides information about the product geophysical data content, the file naming convention, data format and metadata, the product grid and geographic projection, known limitations of the product and available software tools for decoding and interpreting the data.

1.2 Document Structure

This document is structured as follows:

- Chapter 1: introduction.
- Chapter 2-8: product information for each product, respectively: Surface Elevation Change (SEC), Ice Velocity (IV) from SAR, Ice Velocity (IV) from Optical, Gravimetric Mass Balance (GMB), Mass Flow rate and Ice Discharge (MFID), Supraglacial Lakes (SG) and Calving Front Locations (CFL).

1.3 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	ESA/Contract No. 4000126023/19/I-NB, and its Appendix 1	CCI+ PHASE 1 - NEW R&D ON CCI ECVS, for Greenland_Ice Sheet_cci	2019.04.01	
AD2	ESA-CCI-EOPS-PRGM-SOW-18-0118 Appendix 2 to contract.	Climate Change Initiative Extension (CCI+) Phase 1, New R&D on CCI ECVs Statement of Work	2018.05.31	Issue 1 Revision 6

Table 1.2: List of Reference Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
RD1	ST-DTU-ESA-GISCCI+-PUG-001	Product User Guide (PUG)	2017.11.23	2.2
RD2	ST-DTU-ESA-GISCCI+-ATBD-001	Greenland_Ice_Sheet_cci+ Algorithm Theoretical Basis Document (ATBD) for CCI+ Phase 1	2020.05.05	1.1

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

2 Surface elevation change

2.1 Product Geophysical Data Content

This chapter describes the Surface Elevation Change ECV parameter products, based on radar altimetry measurements from ERS-1, ERS-2, ENVISAT, CryoSat-2, and Sentinel-3. The Surface Elevation Change product contains dH/dt estimates and their associated errors for the Greenland Ice Sheet in 5x5 km polar stereographic grid. Estimates are provided for the period 1992-2019 (both years included), in 5-yearly running means. The algorithms used to derive the SEC product are explained in detail in Simonsen and Sørensen (2017), and Sørensen et al. (2018). The approach used here is the most optimal combination of the XO-, TR-, and PF-algorithm; the data are corrected for both backscatter and leading-edge width, and solved at 1 km grid resolution and averaged in the post-processing to 5 km grid resolution by ordinary kriging. The variables available are provided in Table 2.1.

Table 2.1: Available variables for SEC.

Short name	Long name	Unit	Description
SEC	Rate of surface elevation change	m/year	Observed surface elevation change for a 5-yearly running means window.
SECer	Error of rate of surface elevation change	m/year	Error associated with the SEC
Time	Midpoint time of acquisitions used	Hours since 01-01-1991	The timestamp for the mid of the 5-yearly running means window.
Start_time	Time of first observation	Hours since 01-01-1991	The date of the first satellite data used in the SEC estimate
End_time	Time of last observation	Hours since 01-01-1991	The date of the last satellite data used in the SEC estimate

2.2 Product Data Format

The Surface Elevation Change (SEC) version 2.0 product contains two different types of data files:

1) png plots of the surface elevation changes and error.

2) NetCDF file containing the surface elevation changes and their associated errors.

Data are based on ESAs Ku-band radar satellite level-2 data products and provided in 5-year means at 5 km grid resolution.

The NetCDF file contains the following global attributes to be compliant with the ESA CCI standard:

```
netcdf file: CCI_GrIS_RA_SEC_5km_Vers2.0_2020-08-26.nc {
 dimensions:
   x = 325;
   t = 24;
   y = 614;
 variables:
   float x(x=325);
     :long_name = "Cartesian x-coordinate - easting";
```

```
  :standard_name = "projection_x_coordinate";
  :units = "m";

float y(y=614);
  :standard_name = "projection_y_coordinate";
  :long_name = "Cartesian y-coordinate - northing";
  :units = "m";

float Start_time(t=24);
  :long_name = "Time of first observation";
  :standard_name = "Start_time";
  :units = "hours since 1990-01-01T00:00:00Z";
  :calendar = "standard";

float time(t=24);
  :long_name = "Midpoint time of acquisitions used";
  :standard_name = "time";
  :units = "hours since 1990-01-01T00:00:00Z";

float End_time(t=24);
  :long_name = "Time of last observation";
  :standard_name = "End_time";
  :units = "hours since 1990-01-01T00:00:00Z";

char crs;
  :ellipsoid = "WGS84";
  :false_easting = 0.0; // double
  :false_northing = 0.0; // double
  :grid_mapping_name = "polar_stereographic";
  :latitude_of_projection_origin = 90.0; // double
  :standard_parallel = 70.0; // double
  :straight_vertical_longitude_from_pole = -45.0; // double
  :EPSG = "3413";

float lat(y=614, x=325);
  :_FillValue = 9999.0f; // float
  :units = "degrees_north";
  :grid_mapping = "crs";
  :long_name = "Latitude";
  :_ChunkSizes = 614, 325; // int

float lon(y=614, x=325);
  :_FillValue = 9999.0f; // float
  :units = "degrees_east";
```

```
    :grid_mapping = "crs";
    :long_name = "longitude";
    :_ChunkSizes = 614, 325; // int

  float SEC(y=614, x=325, t=24);
    :_FillValue = NaNf; // float
    :long_name = "Rate of surface elevation change";
    :grid_mapping = "crs";
    :coordinates = "y x time";
    :units = "m/year";
    :_ChunkSizes = 307, 163, 12; // int

  float SECer(y=614, x=325, t=24);
    :_FillValue = NaNf; // float
    :long_name = "Error of rate of surface elevation change";
    :grid_mapping = "crs";
    :coordinates = "y x time";
    :units = "m/year";
    :_ChunkSizes = 307, 163, 12; // int

// global attributes:
:_NCProperties = "version=1|netcdflibversion=4.6.1|hdf5libversion=1.10.2";
:Title = "Surface elevation change of the Greenland ice sheet from radar altimetry";
:institution = "DTU Space (GEO) for ESA Greenland CCI+";
:references = "Simonsen and Sørensen (2017), Sørensen et al. (2018)";
:source = "ERS-1, ERS-2, ENVISAT, CRYOSAT-2, SENTINEL-3A/B";
:history = "git-date 2020-08-26 13:53:31 git-commit eea6c279131cb12b15b5a0ecfb0d342eb6a4e479";
:id = "CCI_GrIS_RA_SEC_5km_Vers2.0_2020-08-26.nc";
:comment = "This data was prepared by DTU space as a part of the ESA Greenland CCI project";
:keywords_vocabulary = "NASA Global Change Master Directory (GCMD) Science Keywords";
:creator_name = "DTU Space - DTU Space - Geodesy and Earth Observation";
:creator_email = "ssim@space.dtu.dk";
:creator_url = "Error! Hyperlink reference not valid.";
:date_created = "2020-08-26";
:project = "Climate Change Initiative -European Space Agency";
:region = "Greenland";
:platform = "ESA Radar altimeters: ERS-1, ERS-2, Envisat, CryoSat-2 and Sentinel-3";
:sensor = "Radar Altimeters carried on ERS-1 ERS-2, ENVISAT, CRYOSAT-2, SENTINEL-3A/B";
:methods_used = "Optimal combination of XO, TR, and PF";
:model_type = "See ATBD";
:grid_projection = "EPSG:3413";
:grid_minx = -739301.6214372054; // double
:grid_miny = -3478140.668199717; // double
```

```
  :grid_nx = 325L; // long
  :grid_ny = 614L; // long
  :grid_cell_width_x = "5000 m";
  :grid_cell_width_y = "5000.0m";
  :geospatial_lat_min = 57.72587420304192; // double
  :geospatial_lat_max = 86.18752713565534; // double
  :geospatial_lon_min = -105.80242378491172; // double
  :geospatial_lon_max = 19.86845657515904; // double
  :geospatial_vertical_min = "0.0";
  :geospatial_vertical_max = "0.0";
  :spatial_resolution = "5000 m";
  :time_coverage_start = "1992";
  :time_coverage_end = "2015";
  :time_coverage_duration = "23";
  :time_coverage_resolution = "1 year";
  :tracking_id = "9fd46e17-596d-43eb-86a7-cafb75665671";
  :netCDF_version = "NETCDF4";
  :product_version = "2.0";
  :doi = "10.11583/DTU.12866000";
  :Conventions = "CF-1.7";
  :format_version = "CCI Data Standards v2.2";
  :license = "ESA CCI Data Policy: free and open access";
  :naming_authority = "DTU space";
  :cdm_data_type = "Grid";
  :key_variables = "SEC, SECer";
  :keywords = "EARTH SCIENCE CRYOSPHERE GLACIERS/ICE SHEETS/GLACIER ELEVATION/ICE SHEET ELEVATION";
  :standard_name_vocabulary = "NetCDF Climate and Forecast (CF) Metadata Conventions Version 1.7";
  :summary = "Surface elevation change rate derived for Greenland in 5km by 5km grid cells over a 5/5 year window moving monthly cadence.";
}
```

2.3 File naming convention

All 5-year SEC grids are provided in one netCDF file named CCI_GrIS_RA_SEC_5km_Vers2.0_2020-08-26.nc

The figures are provided in png files named GrIS_SEC_XXXX_YYYY.png, with XXXX being the start year and YYYY being the end year. Both years are included.

2.4 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. This information is also available within the NetCDF-file in the crs-variable.

2.5 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 (ATBD document). Outliers in the mountainous coastal regions are unavoidable and apparent in the products.

2.6 Available Software Tools

The Ice Sheets CCI surface elevation change product is distributed as 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.

Panoply (https://www.giss.nasa.gov/tools/panoply/) can be used to easily view and visualize data in a netCDF file.

2.7 References

Simonsen, S. B., and Sørensen, L. S. (2017) 'Implications of changing scattering properties on Greenland ice sheet volume change from Cryosat-2 altimetry', Remote Sensing of Environment. Elsevier Inc., 190, pp. 207–216. DOI: 10.1016/j.rse.2016.12.012.

Sørensen, L. S., Simonsen, S. B., Forsberg, R., Khvorostovsky, K., Meister, R., and Engdahl, M. E. (2018) '25 years of elevation changes of the Greenland Ice Sheet from ERS, Envisat, and CryoSat-2 radar altimetry', Earth and Planetary Science Letters, 495, pp. 234-241 DOI: 10.1016/j.epsl.2018.05.015

3 Ice Velocity (SAR)

3.1 Product Geophysical Data Content

The Ice Velocity (IV) SAR products provide surface velocity maps of the Greenland Ice Sheet derived from synthetic aperture radar (SAR) satellites applying both offset tracking and InSAR techniques (Figure 3.1). The primary processors used by DTU (IPP) and ENVEO (ESP v2.1) are state-of-the-art IV retrieval algorithms designed for SAR sensors (e.g. Sentinel-1, TerraSAR-X, ALOS PALSAR, Cosmo-SkyMed), and have been tested rigorously through intercomparisons with other packages and extensive validation efforts. The latest products are derived using data from the Copernicus Sentinel-1 mission (S-1), which provides continuous coverage since October 2014. Dedicated ice sheet wide winter mapping campaigns augment the continuous time series of the margins and provide ice velocity in Greenland averaged over periods ranging from 6-days to one year. The averaged Greenland wide products based on offset-tracking combine all ice velocity maps acquired over a full year (Oct-Sep) or mapping campaign (Dec-Jan) and are provided at 250m grid spacing. The InSAR products, derived using both ascending and descending crossing orbit pairs acquired in Interferometric Wide (IW) swath mode, are provided at 100m. All products are provided in NetCDF format containing separate layers for the velocity components as well as the velocity magnitude, valid pixel count and error standard deviation.

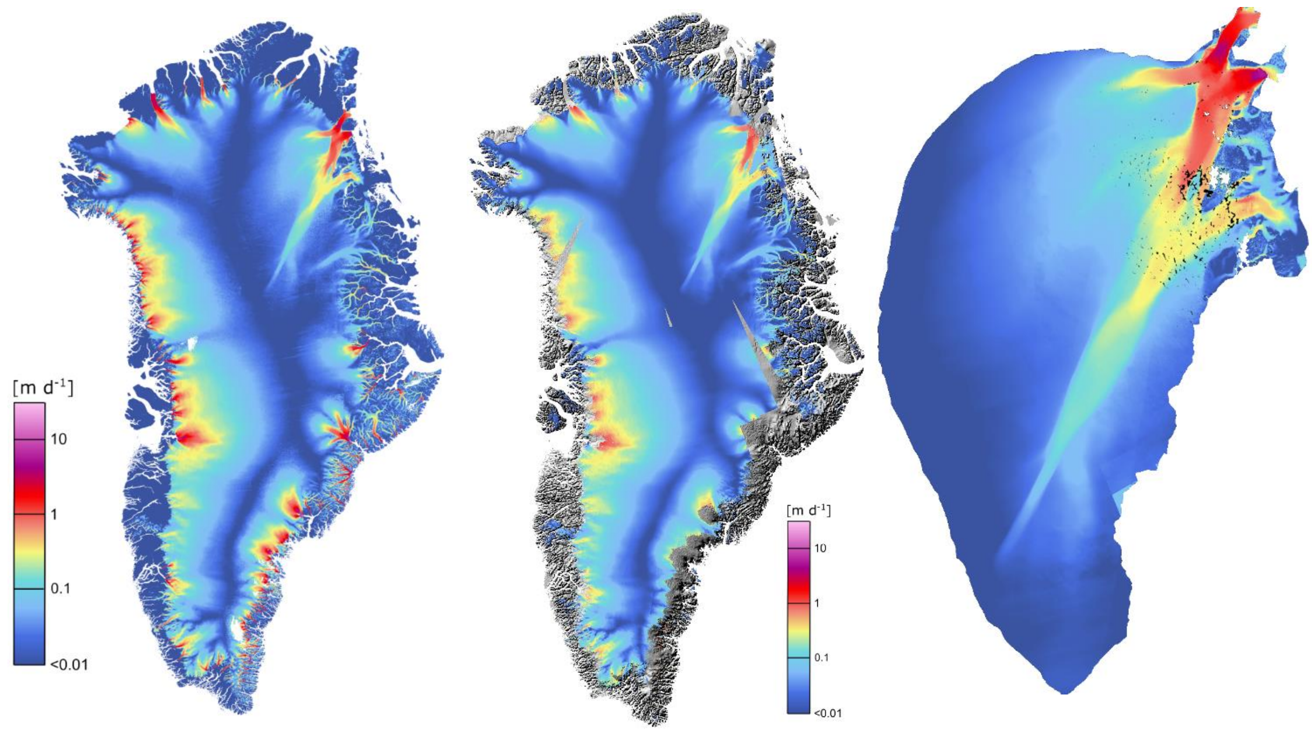

Figure 3.1: Left) Ice velocity map of the Greenland Ice Sheet based on offset-tracking processing of Sentinel-1 data acquired during the 2019/20 winter mapping campaign from December 14, 2019, to January 31, 2020. Center: Ice velocity map of the Greenland Ice Sheet based on interferometric processing of Sentinel-1 data acquired during the 2018/2019, 2019/20 and 2020/21 winter mapping campaigns. Right: InSAR/offset-tracking map of Zwally Basin 2.1 between 2019-12-16 and 2020-01-25 from Sentinel-1.

3.2 Product Data Format

The IV product is provided in a zip file containing the ice velocity map as a NetCDF file with separate layers for the velocity components: vx, vy, vz and vv (magnitude of the horizontal components), and maps with the valid pixel count and uncertainty (std) (Table 1.1). The product metadata is included in the NetCDF file. For all maps, a nodata value of 3.4028235e+38 is used. Also included in the zip folder is a README and DESCRIPTION file as well as a quicklook image.

Table 3.1: IV main data variables

Variable name	Variable description [unit]	Data Type
land_ice_surface_easting_velocity	IV East component [m/day]	32-bit floating-point
land_ice_surface_northing_velocity	IV North component [m/day]	32-bit floating-point
land_ice_surface_vertical_velocity	IV Vertical component [m/day]	32-bit floating-point
land_ice_surface_velocity_magnitude	Ice velocity magnitude [m/day]	32-bit floating-point
land_ice_surface_measurement_count	Valid pixel count [#]	32-bit integer
land_ice_surface_easting_stddev	Std. of the Ve component [m/day]	32-bit floating-point
land_ice_surface_northing_stddev	Std of the Vn component [m/day]	32-bit floating-point

3.3 File naming convention

The file naming convention of the IV Products reflects the region, parameter, grid spacing, platform, method, start and end dates and processing version number (Table 3.2). If the method is omitted, then the default method is offset-tracking.

Table 3.2: Product nomenclature

greenland	Region (Greenland Ice Sheet)
iv	Parameter (Ice Velocity)
250m	Grid Spacing
s1	Platform (S1=Sentinel-1)
insar	Method (optional)
<startdate>	Date of first acquisition
<enddate>	Date of last acquisition
<version>	Version of the product in the format vMAJOR_MINOR
nc	Fileformat (nc: NetCDF)

Example: greenland_iv_250m_s1_20191214_20200131_v1_3.nc, Explanation: Greenland Ice Sheet surface velocity derived from Sentinel-1 averaged for Dec 14th, 2019 – Jan 31th, 2020 and provided at 250m grid spacing, processing version 1.3.

3.4 Product Grid and Projection

The Greenland-wide offset-tracking and interferometric IV maps are provided respectively at 250m x 250m and 100m x 100m grid spacing in North Polar Stereographic projection (EPSG: 3413, defined at https://epsg.io/3413). The horizontal velocity is provided in true meters per day, towards easting (v_x) and northing (v_y) direction of the grid, and the vertical displacement (v_z), is derived from a digital elevation model (TanDEM-X 90m DEM; Rizzoli et al., 2017).

3.5 Product Known Limitations

The following lists some known product limitations:

1. The IV products contain separate layers for the horizontal (Easting, Northing) and the vertical components of velocity. This is, however, not the true 3D velocity, which requires both ascending and descending image pairs acquired close in time. The vertical component is derived from the difference in height of start and end position of the displacement vector taken from a DEM.
2. The IV products do not have a time stamp for a single date but give the average velocity over the time-period covered.
3. For various reasons, the tracking software sometimes fails to find matching features leading to gaps in the velocity fields. This can be caused by a lack of surface features or when features, for example crevasses, rapidly change due to shearing leading to low correlation. Other reasons for gaps in the IV maps can be areas affected by radar shadow or anomalous pixels that are filtered out. A simple distance-weighted averaging filter is applied to get rid of outliers and to fill small gaps in the data (<5 pixels), further filtering/gap filling is left to the user if required. The annual map has only a few gaps.
4. Due to different acquisition modes, sensor type, resolution and processing strategy there can be differences between S-1 IV products and IV products derived from other sensors that complicate a direct comparison between the data sets. Because of differences in resolution, the image patches used for feature tracking have different dimensions impacting the type of features that can be resolved. S-1 for instance does not capture the high velocity gradients that may be found in shear zones with the same detail as for example TerraSAR-X (TSX). On the other hand, due to the regular repeat acquisition the temporal sequence of S-1 is much higher than that of TSX and the covered area of the IV maps is much larger.
5. In-situ GPS data for validation of ice velocity are only sparsely available. We therefore also intercompare the velocity products with ice velocity maps retrieved from other sensors (e.g. S-1 vs TSX) to estimate product performance and uncertainty. As an additional quality test, velocity results on stable terrain (rock outcrops), where no movement is expected, are analysed. This provides a good overall indication of the bias introduced in the end-to-end velocity processing chain including co-registration of images, velocity retrieval, etc. As no external validation data sets are available yet for the latest 2019/20 winter mapping campaign, for this product only the stable terrain analysis has been done.
6. The Greenland-wide interferometric product is an average of data over several winters. The density and coverage of the acquisitions may vary from one winter to the other, hence giving spatially variable weight to each winter dataset.
7. The velocity field derivation from interferometric data requires acquisitions along both ascending and descending directions. Sentinel-1 crossing orbits acquisitions are not available throughout the entire Greenland Ice Sheet and some minor gaps are left in the coverage. In regions of fast flow and shearing, interferometry performs poorly. Most of these areas are masked out during the processing, leaving some gaps in the final product. Some erroneous estimates may nevertheless remain locally in the velocity field.

3.6 Available Software Tools

The Ice Sheets CCI+ ice velocity products are distributed in a NetCDF4 file, following CF-Metadata conventions, such that it can be readily ingested and displayed by any GIS package (e.g. the popular open-source GIS package QGIS).

3.7 References

Nagler, T., Rott, H., Hetzenecker, M., Wuite, J., Potin, P. The Sentinel-1 Mission: New Opportunities for Ice Sheet Observations. Remote Sens. 2015, 7, 9371-9389.

Rizzoli, P., Martone, M., Gonzalez, C., Wecklich, C., Tridon, D.B., Bräutigam, B., Bachmann, M., Schulze, D., Fritz, T., Huber, M. and Wessel, B., (2017). Generation and performance assessment of the global TanDEM-X digital elevation model. ISPRS Journal of Photogrammetry and Remote Sensing, 132, pp.119-139.

4 Ice Velocity (Optical)

4.1 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. All quantities are expressed in meters per day. The resolution of the products is 250m. A high-resolution version (50m) is available upon request. If interested, please contact Daniele Fantin (fantin@stcorp.no).

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 4.1.

Table 4.1: optical 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]
rms_mean	Root mean square

Optical ice velocity time series for a total of 9 major outlet glaciers are made available for summer 2019. The 9 glaciers are Jakobshavn, Upernavik, Petermann, Hagen, 79 fjord and Zachariæ (merged in a single product), Kangerlussuaq, Strorstrømmen and Helheim. Their location over Greenland Ice Sheet is visualised in Figure 4.1.

Figure 4.1: Locations of the 9 large outlet glaciers for which optical IV products are available.

4.2 Product Data Format

The Ice Sheets CCI ice velocity products are distributed in a netCDF4 file. Figure 4.2 shows the file format.

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 horizontal easting and northing components are averaged in time weighted by the (inverse) root mean square (RMS) velocity difference of each pixel with respect to its 5x5 nearest neighbours. The root mean square, *rms_mean* is also provided as an error estimate.

Only a single time slice is provided per NetCDF4, although a product may contain several products with a shorter time range, thus building up a time series. For each NetCDF4, 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. 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 (bnds), where bnds=2. Thus, the velocity grid represents a weighted average velocity over the period between these bounds.

```
netcdf greenland_iv_seasonal_250m_s2_20190630_20190829_Petermann_v2_0 {

dimensions:
        bnds = 2 ;
        x = 536 ;
        y = 535 ;
        time = 1 ;
variables:
        double time(time);
                time:long_name = "Midpoint time of aquisition used" ;
                time:units = "days since 1990-01-01 00:00:00 UTC" ;
                time:standard_name = "time" ;
                time:bounds = "time_bnds" ;
                double time_bnds(time, bnds) ;
                time_bnds:units = "days since 1990-01-01 00:00:00 UTC" ;
                int crs ;
                crs:grid_mapping_name = "polar_stereographic" ;
                crs:standard_parallel = 70. ;
                crs:straight_vertical_longitude_from_pole = 45. ;
                crs:latitude_of_projection_origin = 90. ;
                crs:false_easting = 0. ;
                crs:false_northing = 0. ;
                crs:unit = "m" ;
                crs:epsg = 3413LL ;
                crs:GeoTransform = "-332400.0 50.0 0.0 -923300.0 0.0 -50.0" ;
                char polar_stereographic ;
                polar_stereographic:grid_mapping_name = "polar_stereographic" ;
                polar_stereographic:straight_vertical_longitude_from_pole = -45. ;
                polar_stereographic:false_easting = 0. ;
                polar_stereographic:false_northing = 0. ;
                polar_stereographic:latitude_of_projection_origin = 90. ;
                polar_stereographic:standard_parallel = 70. ;
                polar_stereographic:long_name = "CRS definition" ;
                polar_stereographic:longitude_of_prime_meridian = 0. ;
                polar_stereographic:semi_major_axis = 6378137. ;
                polar_stereographic:inverse_flattening = 298.257223563 ;
                polar_stereographic:GeoTransform = "-332500 250 0 -923500 0 -250 " ;

        double x(x);
                x:standard_name = "projection_x_coordinate" ;
                x:long_name = "x coordinate of projection" ;
                x:units = "m" ;

        double y(y);
                y:standard_name = "projection_y_coordinate" ;
                y:long_name = "y coordinate of projection" ;
                y:units = "m" ;

        float land_ice_surface_easting_velocity(time, y, x) ;
                land_ice_surface_easting_velocity:_FillValue = NaNf ;
                land_ice_surface_easting_velocity:long_name = "land_ice_surface_easting_velocity" ;
                land_ice_surface_easting_velocity:description = "easting ice velocity" ;
```

```
                land_ice_surface_easting_velocity:grid_mapping = "polar_stereographic" ;
                land_ice_surface_easting_velocity:standard_name = "land_ice_surface_easting_velocity" ;
                land_ice_surface_easting_velocity:units = "m/day" ;

        float land_ice_surface_northing_velocity(time, y, x) ;
                land_ice_surface_northing_velocity:_FillValue = NaNf ;
                land_ice_surface_northing_velocity:long_name = "land_ice_surface_northing_velocity" ;
                land_ice_surface_northing_velocity:description = "northing ice velocity" ;
                land_ice_surface_northing_velocity:grid_mapping = "polar_stereographic" ;
                land_ice_surface_northing_velocity:standard_name = "land_ice_surface_northing_velocity" ;
                land_ice_surface_northing_velocity:units = "m/day" ;

        double rms_mean(time, y, x) ;
                rms_mean:_FillValue = 9.96920996838687e+36 ;
                rms_mean:long_name = "arithmetic mean of RMS" ;
                rms_mean:grid_mapping = "polar_stereographic" ;
                rms_mean:standard_name = "mean_rms" ;

// global attributes:
        :product_version = "2.0" ;
        :date_created = "2020-08-09" ;
        :institution = "S[&]T" ;
        :project = "ESA Greenland Ice Sheet CCI+" ;
        :tracking_id = "a7a422f0-6635-11ea-a369-d3543f14ceb6" ;
        :time_coverage_start = "2019-06-30" ;
        :time_coverage_end = "2019-08-29" ;
        :source = "Sentinel-2" ;
        :sensors_used = "Sentinel-2 MSI" ;
        :band_used = "B02" ;
        :method_used = "Offset-tracking" ;
        :netCDF_version = "NetCDF-4 classic" ;
        :units = "m/day" ;
        :resolution = "250.0" ;
        :Conventions = "CF-1.0" ;
```

Figure 4.2: NetCDF file format used in IV products.

4.3 File naming convention

The NetCDF4 uses the following naming convention:

<indicative date>-ESACCI-L3-GIS_IV-S2-<resolution>m-<glacier>-<duration in days>D-v<version>.nc

- <indicative date>: Start date of first Sentinel-2 acquisition.
- ESACCI: Project indicator.
- L3: Product level.
- GIS: CCI Project.
- IV: Data type.
- S2: Product string indicating a single data source.
- <resolution>: Grid spacing in meter. Default is 100m.
- <glacier>: Glacier name.
- <duration in days>: Number of days the product spans.
- <version>: Version of the product in the format vMAJOR_MINOR
- nc: Fileformat (nc: NetCDF)

Example of product filename:

20190501_ESACCI-L3-GIS-IV-S2-100m-Jakobshavn-122D-v3.0.nc

4.4 Product Grid and Projection

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

4.5 Product Known Limitations

For product known limitations we refer to the Algorithm Theoretical Baseline Document [RD-2].

4.6 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.

4.7 References

Auxiliary data used in the generation of the Greenland Ice sheet ice velocity products are land/sea/ice masks from PROMICE (Programme for monitoring of the Greeland ice sheet) (Citterio et al., 2013) and The Greenland Ice Mapping Project (GIMP) (Howat et al, 2014).

Citterio, M., & Ahlstrøm, A. P. (2013). Brief communication" The aerophotogrammetric map of Greenland ice masses". The Cryosphere, 7(2), 445.

Howat, I. M., Negrete, A., & Smith, B. E. (2014). The Greenland Ice Mapping Project (GIMP) land classification and surface elevation data sets. The Cryosphere, 8(4), 1509-1518.

5 Gravimetric Mass Balance

5.1 Product Geophysical Data Content

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 and the algorithms and methods in the ATBD.

5.1.1 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) is provided.

5.1.2 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.

5.2 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)

5.3 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 5-1 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	Type	Description
Latitude	Float	Latitude of centre of grid cell (degree)
Longitude	Float	Longitude of centre of grid cell (degree)
Time	Float	Mean of time span (days after 2003-01-01)
Start_time	Float	Start of time span (days after 2003-01-01)
End_time	Float	End of time span (days after 2003-01-01)
GMB_trend	Float	Mass trend (mm water equivalent)

5.4 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.

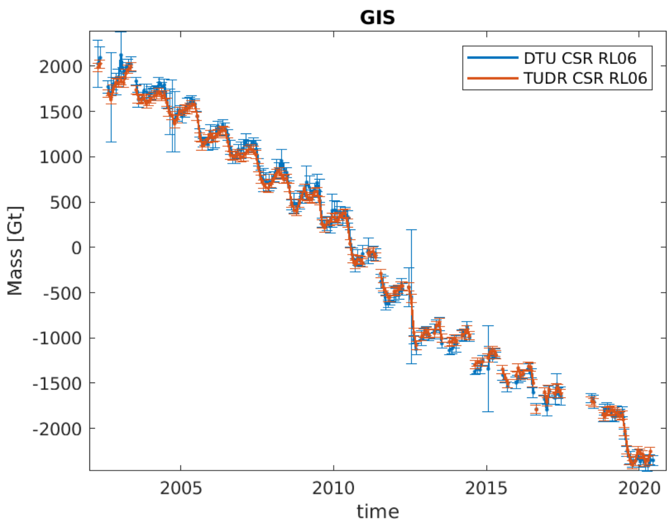

Figure 5.1: Example of total Greenland mass loss time series (basin 00 = GIS)

6 Mass Flow Rate and Ice Discharge

6.1 Product Geophysical Data Content

This chapter describes the mass flow rate and ice discharge (MFID) product. The MFID product is a collection of files that provides an estimate of the solid ice volume flow rate across glacier cross-sections (gates) approximately 10 km upstream from the grounding zone for the majority of Greenland's marine terminating glaciers.

6.2 Product Data Format

The product is provided in CSV format. The first row is the header, with values "Date" and then the sector the discharge, error, or coverage number represents, with sectors from Zwally *et al.* (2012) or Figure 6.1 below. The first column, "Date", in YYYY-MM-DD format is the end of the month of the observation.

Figure 6.1: Greenland Ice Sheet sectors (Zwally *et al.,* 2012).

6.3 File naming convention

We use the following file naming convention:

1. MFID.csv: Mass flow rate ice discharge. Units are Gt yr^{-1}.
2. MFID_err.csv: Mass flow rate ice discharge uncertainty. Units are Gt yr^{-1}.
3. coverage.csv: Coverage for each sector at each timestamp. Unitless [0 to 1].

6.4 Product Grid and Projection

There is no geospatial information for this product.

The product is organized by Zwally *et al.* (2012) sector.

6.5 Product Known Limitations

Only glaciers that flow > 100 m per year both at the terminus and at the gate location are included in this product.

Discharge is estimated at the gate approximately 10 km upstream from the terminus. Processes (e.g. surface melt) between the gate and the terminus are not included.

6.6 Available Software Tools

The products can be viewed by any software capable of reading comma delimited files.

6.7 References

Zwally, H. Jay, Giovinetto, Mario B., Beckley, Matthew A., Saba, Jack L.: Antarctic and Greenland Drainage Systems , 2012, GSFC Cryospheric Sciences Laboratory

Mankoff, Kenneth D., Solgaard, Anne, Colgan, William, Ahlstrøm, Andreas P., Khan, Shfaqat Abbas, Fausto, Robert S.: Greenland Ice Sheet solid ice discharge from 1986 through March 2020 , Earth System Science Data 12(2), Copernicus GmbH, 1367–1383, 6 2020

7 Supraglacial Lakes

7.1 Product Geophysical Data Content

This chapter describes the supraglacial lakes (SGL) products. The SGL product is a collection of vector files delineating supraglacial water bodies in the Sermeq Kujalleq (SK, also known as Jakobshavn Isbræ) and Nioghalvfjerdsbræ (79N, also known as 79N Glacier) catchments at each available time step during the 2019 melt season from 1st May to 1st October. The catchments are defined as the glacier hydrological catchments described by Mankoff et al. (2020).

Each supraglacial water body was detected from freely available Sentinel-2A/2B imagery, using an adaptation of the method adopted by Yang and Smith (2013) and Yang (2019). This was refined for batch processing and specific file handling procedures in line with the CCI+ project guidelines. The detection method largely utilises the ArcGIS python package ArcPy for detecting lakes from generated NDWI raster files.

7.2 Product Data Format

The following files are within each distributed product:

- A zip folder containing supraglacial lake shapefiles for each time step
- A compiled shapefile containing all supraglacial lake features for all time steps
- A csv file containing general statistics on the detected supraglacial lakes, including total lake count and area, and lake count and area for each Sentinel-2 scene tile that lakes were detected from
- A pdf file on the study of supraglacial lake change in the given catchment, including time-series analysis, comparison to ice velocity, elevation analysis, and lake cluster analysis

The data format is standard ESRI polygon shapefile in latitude and longitude (WGS 84) projection. Data from the SK and 79N catchments are given as both a collection of shapefiles, where each shapefile represents a time step, and as a single shapefile containing all detected lakes from every time step. Each water body polygon has seven assigned attributes, as detailed in Table 7.1.

Table 7.1: Product Metadata for supraglacial lakes.

Attribute name	Format	Attribute description
id1	Integer	Identification number of the water body. If the water body coincides with a pre-determined sink (calculated from ArcticDEM) then the identification number will correspond with the sink. Water bodies corresponding to a sink will have consistent identification throughout the dataset. If the water body does not correspond with a pre-determined sink, the water body is assigned a sequential identification number.
date	Date	Date of the satellite image from which the water body was detected, formatted as yyyymmdd.
area1	Float	Area of the water body in sq km, given to four decimal places.
elev	Float	Elevation of the water body (metres a.s.l.), determined as the ArcticDEM elevation coinciding with the centroid point of the water body.
source	Text	Source of the satellite image from which the water body was detected from (S2A/S2B).
tile	Text	Satellite image tile from which the water body was detected from.
row	Text	Satellite image row from which the water body was detected from.

7.3 File naming convention

Within each collection of shapefiles, files are named in the following format: 'yyyymmdd_lakes.shp'. The given date denotes the time step from which the supraglacial water bodies were detected.

In the merged shapefile, the files are named according to the project name, data product and version – 'cciplus_supralakes_version.shp'.

7.4 Product Grid and Projection

The primary product is an ESRI polygon shapefile in Universal Transverse Mercator (UTM) Zone 22N projection (EPSG: 32622).

7.5 Product Known Limitations

Water body detection is limited by ice cover, sediment and saturated snow conditions at certain times in the melt season. This is addressed using a dual binary threshold in the spectral indices processing, which identifies the upper and lower extent of each detected water body. If a supraglacial lake is present for both threshold then the upper extent is retained, which will best compensate for ice-covered lakes and lakes with accumulated sediment at the bottom, and reduce the probability of false matches in regions of saturated snow.

7.6 Available Software Tools

The SGL product is distributed as ESRI shapefiles, which is a standard format for vector data, and readable by most open source (e.g. QGIS: www.qgis.org) or commercial GIS software (e.g. ArcGIS). The shapefiles contain metadata information, and information on the optical satellite data using for production.

7.7 References

Mankoff, K. et al. (2020) High resolution map of Greenland hydrologic outlets, basins, and streams, and a 1979 through 2017 time series of Greenland liquid water runoff for each outlet. Version 1. *https://promice.org/PromiceDataPortal/api/download/0f9dc69b-2e3c-43a2-a928-36fbb88d7433*.

Yang, K. (2019) Supraglacial river and lake analysis [software]. *figshare.* doi:10.6084/m9.figshare.9758051.v1.

Yang, K. & Smith, L. (2013) Supraglacial streams on the Greenland Ice Sheet delineated from combined spectral-shape information in high-resolution satellite imagery. *IEEE Geosci. Remote Sens. Lett.,* **10** (4), 801- 805.

8 Calving Front Locations

8.1 Product Geophysical Data Content

The CFL product is a collection of annotated GeoJSON files shapefile delineating the CFLs of key outlet glaciers (Hagen, Humboldt, Jakobshavn, Upernavik A, E and F, and Zachariae) for Year 2019 and 2020 (Figure 8.1). The format is standard GeoJSON in latitude and longitude (WGS84) projection. The main attributes are shown in Section 8.2. The basic data are vector line files (not polygons).

Figure 8.1: Key outlet glaciers of Greenland for which CFLs are generated for years 2019 and 2020 with a deep learning based algorithm using Sentinel 2 imagery.

8.1.1 Annual CFLs from Sentinel-2 optical imagery

Annual CFL delineations have been generated from Sentinel-2 for key outlet glaciers (Hagen, Humboldt, Jakobshavn, Upernavik A, E and F, and Zachariae) for Year 2019 and 2020 of the Greenland Ice Sheet, see Figure 8.1.

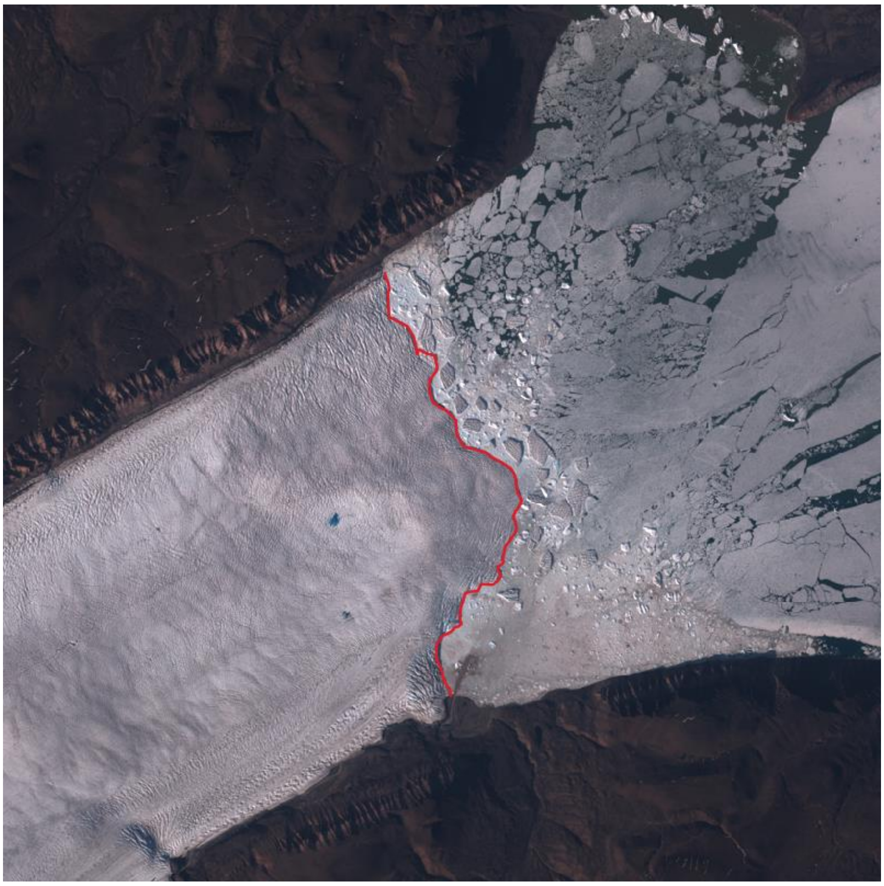

Figure 8.2: Example CFL of the Hagen glacier.

8.1.2 Product Flags and Metadata

At some glacier fronts brash ice and icebergs pile up in front of the main calving front. Unlike the manual delineation, the deep learning algorithm cannot differentiate between ice melange, sea ice, etc. This parameter is not recorded as metadata.

8.2 Product Data Format

The digitised CFL is stored as a series of latitude-longitude vertices stored as a vector line in standard GIS format. Additionally, metadata information on the sensor and processing steps are stored in the corresponding attribute table (Table 8.1).

CFL Line files (CFL, GLL) are stored as GeoJSON files. This ensures consistency with other projects, which also maps outlines of isolated Greenland glaciers.

The CFL product includes 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 8.1 presents the CFL product structure.

Table 8.1: CFL product structure

Shapefile	Attribute	Format	Mandatory	Attribute description
CFL	RC_ID	int	YES	Identification number of the Processing Agency (value set to -1 indicating missing value)
	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: "not used"
	inst_name	varchar(80)	YES	Instrument name (e.g. MSI)
	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 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 metres in general 1 pixel size
	loc_unc_y	numeric(11,4)	YES	Local (within-image) location uncertainty, in metres in general 1 pixel size
	glob_unc_x	numeric(11,4)	YES	Global (geographic) location uncertainty, in metres
	glob_unc_y	numeric(11,4)	YES	Global (geographic) location uncertainty, in metres
	label	char(3)	YES	Where segment is located (trm: terminus)
	orthocorre	char(1)	YES	Ortho-corrected: yes (y), no (n)
glaciers	ID	varchar(20)	YES	Unique glacier ID in the form GnnnnnEmmmmm[N|S]
	name	varchar(40)	NO	Name of glacier, if one exists

8.3 File naming convention

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

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

Table 8.2: Product nomenclature

greenland	Region (Greenland Ice Sheet)
cfl	Parameter (Calving Front Locations)
s2	Platform (S2=Sentinel-2)
<glacier_name>	Common name of the glacier, if exists, otherwise "noname"
<glacier_ID>	GLIMS glacier ID
<date>	Date of acquisition
<version>	Version of the product in the format vMAJOR_MINOR
.shp	Fileformat (shp: shapefile)

For example: The segments shapefile of Helheim glacier which contains the CFL derived from analysis of an image with acquisition time 13:23:35 on the 12th of August 2020 is named as: `greenland_cfl_s2_Helheim_G321627E66422N_20200812_132535_v1_0.geojson`

8.4 Product Grid and Projection

For CFL the primary product is a GeoJSON file in latitude and longitude, WGS84 projection.

8.5 Product Known Limitations

Automatic delineation is sensitive to lack of textures and cloud coverage and the presence of the ice melange in front of the calving cliff. These factors 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 [RD2].

8.6 Available Software Tools

The CFL product is distributed as GeoJSON files, which is a standard format for vector data, and readable by almost all open source (e.g qgis: www.qgis.org) or commercial GIS (ARC-Info, ARC View, etc.) systems or image processing systems (e.g. PCI Geomatics).