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

Greenland_Ice_Sheet_cci+ (GIS_cci+)

Product User Guide (PUG) for CCI+ Phase 2

Prime & Science Lead: Louise Sandberg Sørensen

DTU Space, Copenhagen, Denmark

Technical Officer: Anna Maria Trofaier

ESA ECSAT, Didcot, United Kingdom

Consortium: Asiaq Greenland Survey (ASIAQ)

DTU-Space, Department of Geodynamics (DTU-S)

DTU-Space, Department of Microwaves and Remote Sensing (DTU-N)

Danish Meteorological Institute (DMI)

ENVironmental Earth Observation IT GmbH (ENVEO)

Science [&] Technology AS (S&T)

Technische Universität Dresden (TUDr)

The Geological Survey of Denmark and Greenland (GEUS)

The Niels Bohr Institute (NBI)

Northumbria University (NU)

Signatures page

Prepared by	Anne Solgaard Lead Author, GEUS	
Issued by	Daniele Fantin, Project Manager, S[&]T	
Checked by	Louise Sørensen Science Leader, DTU-S	
Approved by	Anna Maria Trofaier ESA Technical Officer	

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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	
3.0	All	All	Version 3 update for Phase 2	Released to ESA

Acronyms and Abbreviations

Acronyms	Explanation
ATBD	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CFL	Calving Front Location
CONAE	Comisión Nacional de Actividades Espaciales
CS2	CryoSat-2
CSR	Center for Space Research, University of Austin
DEM	Digital Elevation Model
(D)InSAR	(Differential) Interferometric Synthetic Aperture Radar
DL	Deep Learning
DMI	Danish Meteorological Institute
DTU-N	DTU Microwaves and Remote Sensing Group
DTU-S	DTU Geodynamics Group
E3UB	End-to-End ECV Uncertainty Budget
ECV	Essential Climate Variable
ENU	East North Up
ENVEO	ENVironmental Earth Observation IT GmbH
EO	Earth Observation
ESA	European Space Agency
GCOS	Global Climate Observation System
GCP	Ground Control Point

GEUS	Geological Survey of Denmark and Greenland
GFZ	Deutsche GeoForschungsZentrum
GIA	Glacial Isostatic Adjustment
GIS	Greenland Ice Sheet
GLL	Grounding Line Location
GMB	Gravimetry Mass Balance
GRACE(-FO)	The Gravity Recovery and Climate Experiment (Follow On)
IMBIE	Ice Sheet Mass Balance Inter-Comparison Exercise
InSAR	Interferometric Synthetic Aperture Radar
IPP	Interferometric Post-Processing
IV	Ice Velocity
JPL	NASA Jet Propulsion Laboratory
MAI	Multiple Aperture Interferometry
MEaSUREs	Making Earth System Data Records for Use in Research Environments (NASA)
MFID	Mass Flux and Ice Discharge
NBI	Niels Bohr Institute, University of Copenhagen
NEGIS	North East Greenland Ice Stream
NU	Northumbria University
OT	Offset Tracking
PROMICE	Danish Program for Monitoring of the Greenland Ice Sheet
RA	Radar Altimetry
RMS	Root Mean Square
S&T	Science and Technology AS
S2	Sentinel-2

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

1 Introduction

1.1 Purpose and Scope

This document contains the Product User Guide (PUG) for the Greenland_Ice_Sheet_cci (GIS_cci) project for CCI+ Phase 2, 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. In this version of the PUG, we have considered the suggestions for improvements made by ESA CCI+ Climate Modelling User Group (CMUG) in Deliverable 2.3 Suitability of CCI ECVs for Climate Science and Services [AD3].

1.2 Document Structure

This document is structured as follows:

- Chapter 1: introduction.
- Chapter 2-10: product information for each product, respectively: Surface Elevation Change (SEC), the new product Surface Elevation Change (dSEC), Ice Velocity (IV) from SAR imagery, Ice Velocity (IV) from Optical imagery, Gravimetric Mass Balance (GMB), Mass Flow rate and Ice Discharge (MFID), Supraglacial Lakes (SG) and Calving Front Locations (CFL) and the new, experimental Ice uplift/subsidence from InSAR line-of-sight velocity.

1.3 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	ESA/Contract No. 4000126523/19/I-NB - Greenland_Ice-Sheets_CCI+ and its Appendix 1 (incl CCN3)	CCI+ Phase 1 New R&D pm CCI ECVs for Greenland _Ice Sheet_cci (incl CCN3)	Cont: 2019.03.06 CCN3: 2022.12.05	-
AD2	ESA-EOP-SC-AMT-2021-53	Climate Change Initiative Extension (CCI+) Phase 2 - New R&D on CCI Essential Climate Variables -SoW (incl Annexes)	2022.06.10	Issue 1 Revision 2
AD3	D2.3: Suitability of CCI ECVs for Climate Science and Services	Suitability of CCI ECVs for Climate Science and Services	2022.03.28	3.0

Table 1.2: List of Reference Documents

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

RD1	ST-DTU-ESA-GISCCI+-PUG-001 _2.0	Product User Guide (PUG)	2022.02.22	2.0
RD2	ST-DTU-ESA-GISCCI+-ATBD-00 1	Greenland_Ice_Sheet_cci+ Algorithm Theoretical Basis Document (ATBD) for CCI+ Phase 2	01.12.2023	2.0

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

2 Surface elevation change (SEC)

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.

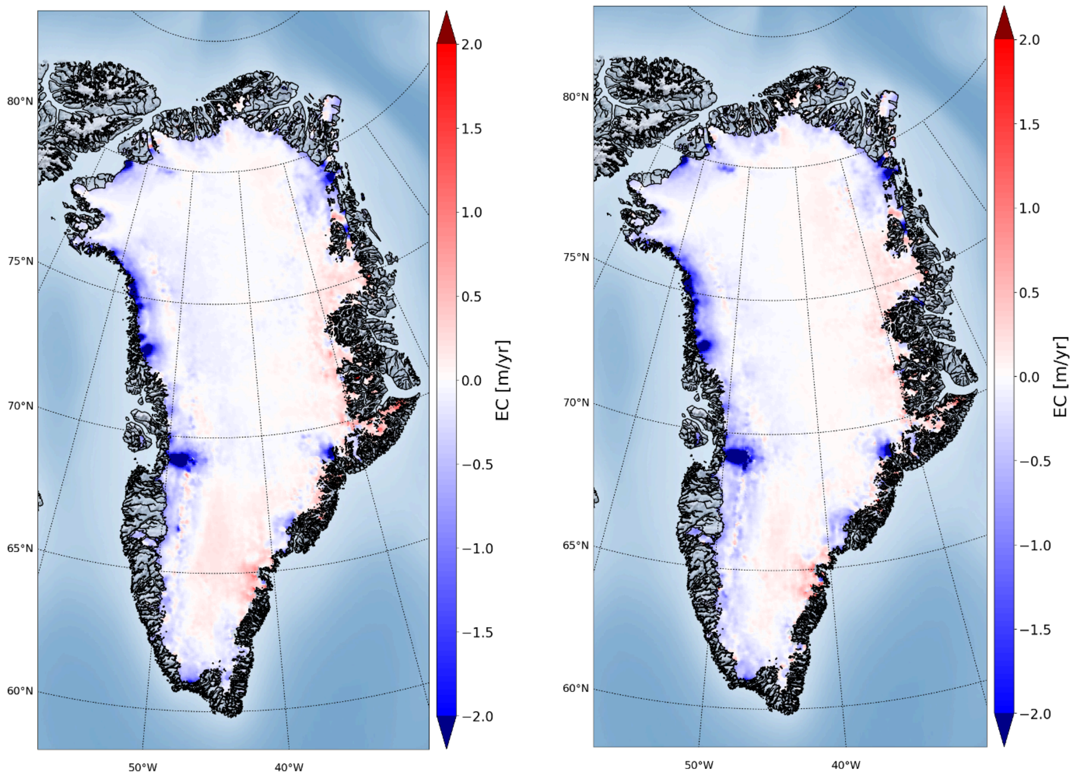

Figure 2.1 : Surface elevation changes on a 5 km grid for the period 2012-2016 (To the left) and 2013-2017 (To the right).

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 is 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_Vers3.0_2024-05-31.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 [RD2]). 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 Monthly Surface Elevation Change (dSEC)

3.1 Product Geophysical Data Content

This chapter describes the Monthly Surface Elevation Change (dSEC) ECV parameter products based on radar altimetry measurements from CryoSat-2, and will evolve into also including Sentinel-3. The Surface Elevation Change product contains dH estimates for the Greenland Ice Sheet in 5x5 km polar stereographic grid. Estimates are provided for 2010-2024 (both years included).

The algorithms used to derive the dSEC product are a state-space model that uses monthly filtered POCA data in a state-space model (Kristensen et al, 2016) to model the ice surface in both the temporal and spatial domains. In the spatial domain, a Gaussian Markov Random Field Framework is used. In the temporal domain, a simple AR-1 process is implemented. The joint precision matrix between these two (using the Kronecker product) is then used to estimate the anomalies in time and space.

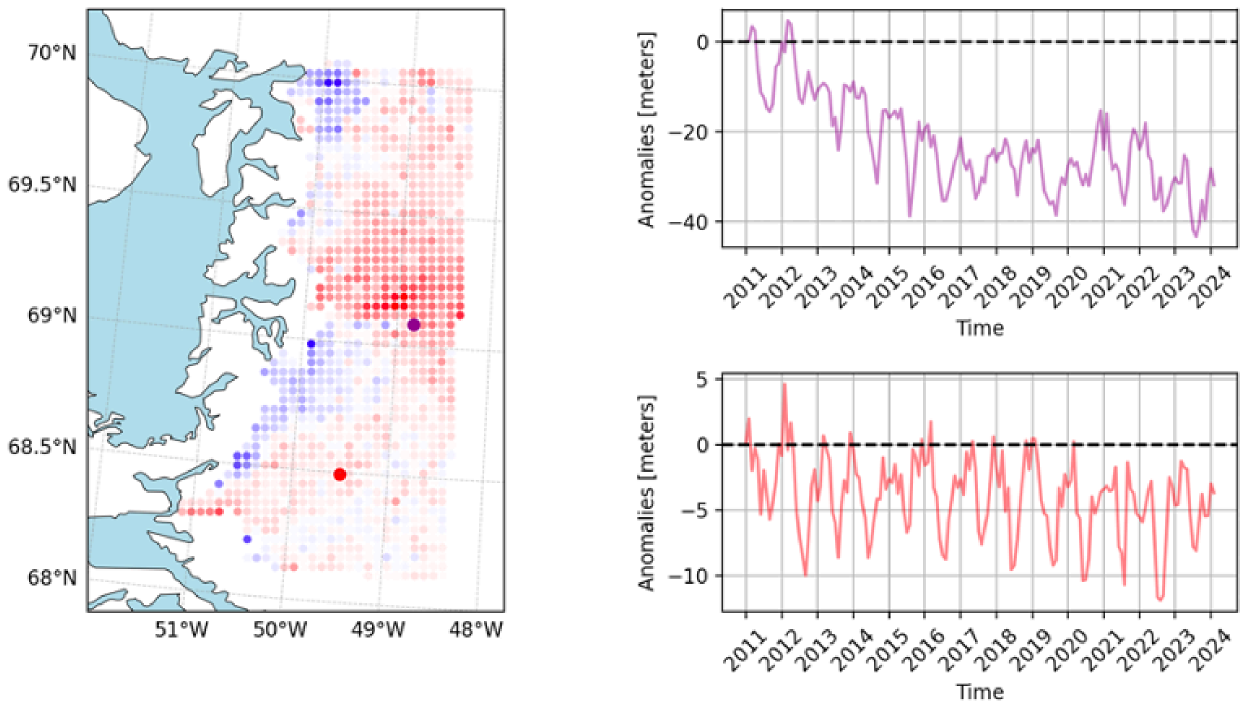

Figure 3.1: Timeseries of ice surface elevation over the region around the outlet glacier from the Greenland ice sheet called Jakobshavn ice stream (purple) and further south from the glacier (red).

The variables available are provided in Table 3.1.

Table 3.1: Available variables for dSEC.

Short name	Long name	Unit	Description
dSEC	Rate of surface elevation change	m/month	Estimated surface elevation change for the grid.
dSECer	Error of rate of surface elevation change	m/month	Error associated with the dSEC

Time	Midpoint time of acquisitions used	Decimal years	The timestamp for the mid of the month.

3.2 Product Data Format

The Monthly Surface Elevation Change (dSEC) version 1.0 product contains the following 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 monthly dh at 5 km grid resolution.

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

```
netcdf file: {
 dimensions:
  id = 6610;
  time = 48;
  Satcode = 13;
 variables:
  float time(time=48);
   :long_name = "time at model point";
   :standard_name = "time";
   :units = "decimal years";

  float ref_surface_elevation(id=6610);
   :long_name = "Reference Surface Elevation";
   :standard_name = "I";
   :units = "meters";

  float ZZ(id=6610, time=48);
   :_ChunkSizes = 6610U, 48U; // uint

  float ZZer(id=6610, time=48);
   :_ChunkSizes = 6610U, 48U; // uint

  int Satcode(Satcode=13);
   :sat4 = "CS2-LRM";
   :sat5 = "CS2-SAR";
   :sat6 = "CS2-SIN";
```

```
    float Lon(id=6610);
      :_ChunkSizes = 6610U; // uint

    float Lat(id=6610);
      :_ChunkSizes = 6610U; // uint

    float XX(id=6610);
      :_ChunkSizes = 6610U; // uint

    float YY(id=6610);
      :_ChunkSizes = 6610U; // uint

  // global attributes:
  :Title = "dSEC solution from DTU-RART";
  :institution = "DTU Space - GEO Div.";
  :Author = "Natalia H. Andersen";
  :contact = "naand@space.dtu.dk";
  :Contributor = "TBD";
  :file_creation_date = "2024-06-07";
  :region = "GrIS";
  :grid_projection = "+proj=stere +lat_0=90 +lat_ts=70 +lon_0=-45 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs";
  :git_Tracking_id = "964ee173c47b9304bea1df1b7e6f32fbbfeeeaf9";
  :netCDF_version = "NETCDF4";
}
```

3.3 File naming convention

All Monthly dSEC grids are provided in one netCDF file named:

CCI_"Area"_RA_dSEC_dh_"resolution"_Vers10_"start year"_"end year".nc

Example: CCI_GrIS_RA_dSEC_dh_5km_Vers10_2010_2024.nc

3.4 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.

3.5 Product Known Limitations

Similar limitations as for the other SEC product. This includes also the penetration depth of the radar beam into various surfaces and the known errors in the highly varying topography in the coastal regions.

3.6 Available Software Tools

The Ice Sheets CCI Monthly surface elevation change product is provided in the form of a NetCDF4-file. Its structure follows the CF-Metadata conventions, making it easily accessible and viewable using standard NetCDF display programs. Additionally, it is designed to be self-explanatory, simplifying the process of understanding its content and format.
Panoply (https://www.giss.nasa.gov/tools/panoply/) can be used to easily view and visualize data in a netCDF file.

3.7 References

Kristensen, K., Nielsen, A., Berg, C. W., Skaug, H., & Bell, B. M. (2016). TMB: Automatic Differentiation and Laplace Approximation. Journal of Statistical Software, 70(5), 1–21. https://doi.org/10.18637/jss.v070.i05

4 Ice Velocity (SAR)

4.1 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, SAOCOM, TerraSAR-X, ALOS PALSAR), 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 of the Greenland Ice Sheet since October 2014. Dedicated ice sheet wide winter mapping campaigns augment the continuous time series of the margins and enable ice velocity retrieval in Greenland averaged over periods ranging from 6-days to multiple years. The averaged Greenland wide products based on offset-tracking combine all ice velocity maps acquired over a month, year (Oct-Sep) or mapping campaign (Dec-Jan/Feb) 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 (vx,vy,vz) as well as the velocity magnitude, valid pixel count and uncertainty.

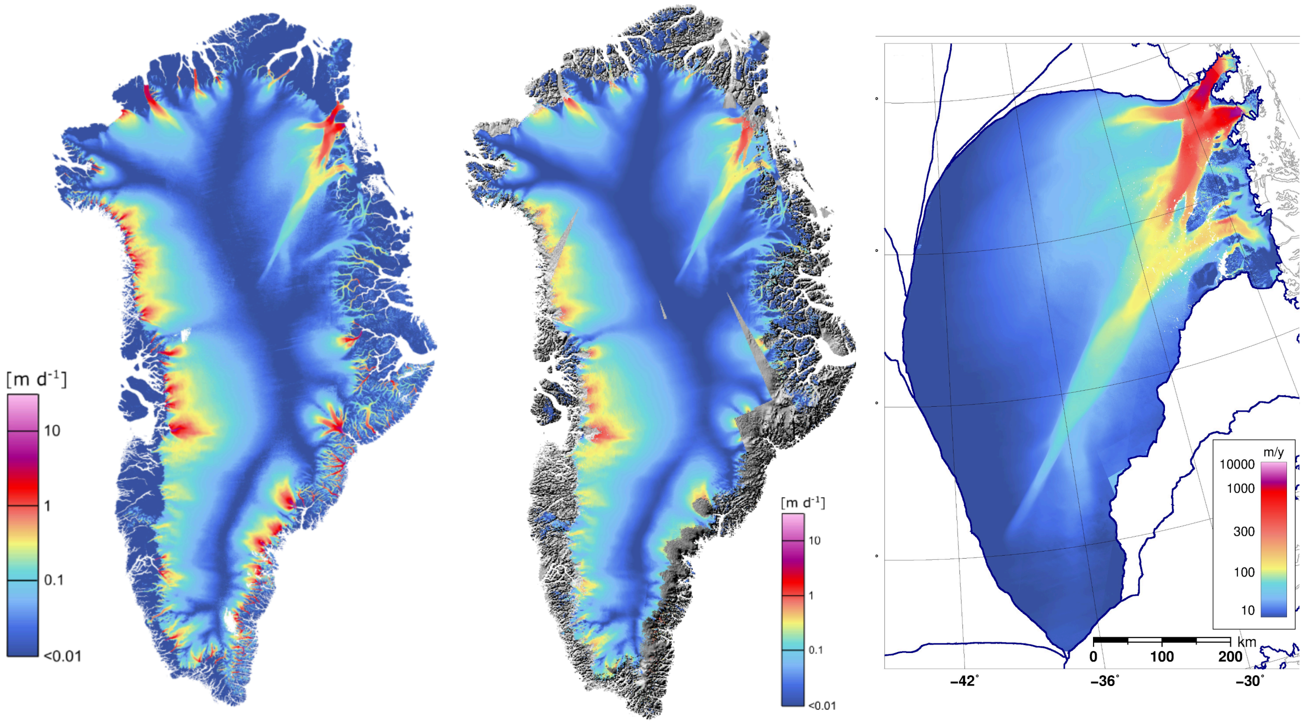

Figure 4.1: Left) Ice velocity map of the Greenland Ice Sheet based on offset-tracking processing of Sentinel-1 data acquired during the 2019/20 winter mapping campaign from December 14, 2019, to January 31, 2020. Center: Ice velocity map of the Greenland Ice Sheet based on interferometric processing 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.

4.2 Product Data Format

The IV products are 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 (standard deviation) (Table 4.1). 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 4.1: 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

4.3 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 4.2). If the method is omitted, then the default method is offset-tracking.

Table 4.2: Product nomenclature

greenland	Region (Greenland Ice Sheet)
iv	Parameter (Ice Velocity)
250m	Grid Spacing
s1	Platform (S1=Sentinel-1)
ot/insar	Method (optional, ot=offset tracking)
<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_20230101_20230131_v1_3.nc, Explanation: Greenland Ice Sheet surface velocity derived from Sentinel-1 averaged for Jan 1st, 2023 – Jan 31st, 2023 and provided at 250m grid spacing, processing version 1.3.

4.4 Product Grid and Projection

The Greenland-wide offset-tracking and interferometric IV maps are provided respectively at 250 m x 250 m and 100 m x 100 m grid spacing in WGS 84 / NSIDC Sea Ice Polar Stereographic North (EPSG: 3413, defined at https://epsg.io/3413). The horizontal velocity is provided in true metres per day, towards easting (v_e) and northing (v_n) 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).

4.5 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. Products may contain 'stripes' or 'streaks' due to ionospheric disturbances, which can, in particular, clearly be seen from visual inspection in slow flow areas. These streaks are often slightly oblique along track and are caused by ionospheric electron density fluctuations leading to varying ionospheric propagation conditions (path delay) during the aperture time (Gray et al., 2000). The velocity error due to ionospheric effects is estimated to be up to 300 m yr^{-1} for single repeat-pairs (Solgaard et al., 2021). Averaging of ice velocity maps as is done in the monthly and annual products usually reduces the impact of the disturbances.

5. Areas that are not covered by ice (e.g. bare land, rock outcrops) are not excluded from the product and have values that are non zero (not NaN). These regions can be used for testing the quality of the product as values should be (close to) zero. If the user wants to remove these areas an ice mask may be useful. For this purpose we recommend the ice sheet outline and glacier inventory data sets from the ESA Glaciers CCI project which provide an inventory of all local (or peripheral) glaciers and ice caps on Greenland (Rastner et al., 2012). The data is available from the Glaciers CCI database website: https://glaciers-cci.enveo.at

6. 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.

7. 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.

8. 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.

9. 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.

4.6 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).

4.7 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.

Gray, A. L., Mattar, K. E., and Sofko, G.: Influence of Ionospheric Electron Density Fluctuations on Satellite Radar Interferometry, Geophysical Research Letters, https://doi.org/10.1029/2000GL000016, 2000.

Rastner, P., Bolch, T., Mölg, N., Machguth, H., Le Bris, R., Paul, F. (2012): The first complete inventory of the local glaciers and ice caps on Greenland. The Cryosphere, 6, 1483-1495. (doi:10.5194/tc-6-1483-2012)

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.

Solgaard, A., Kusk, A., Merryman Boncori, J. P., Dall, J., Mankoff, K. D., Ahlstrøm, A. P., Andersen, S. B., Citterio, M., Karlsson, N. B., Kjeldsen, K. K., Korsgaard, N. J., Larsen, S. H., and Fausto, R. S.: Greenland ice velocity maps from the PROMICE project, Earth Syst. Sci. Data, 13, 3491–3512, https://doi.org/10.5194/essd-13-3491-2021, 2021.

5 Ice Velocity (Optical)

5.1 Product Geophysical Data Content

The optical IV product contains the velocity components in the x and y directions (Figure 5.1). This set of 2 components allows us to calculate the magnitude of the horizontal velocity. All quantities are expressed in meters per day. The resolution of the products is 100 m. A high-resolution version (50 m) 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 5.1.

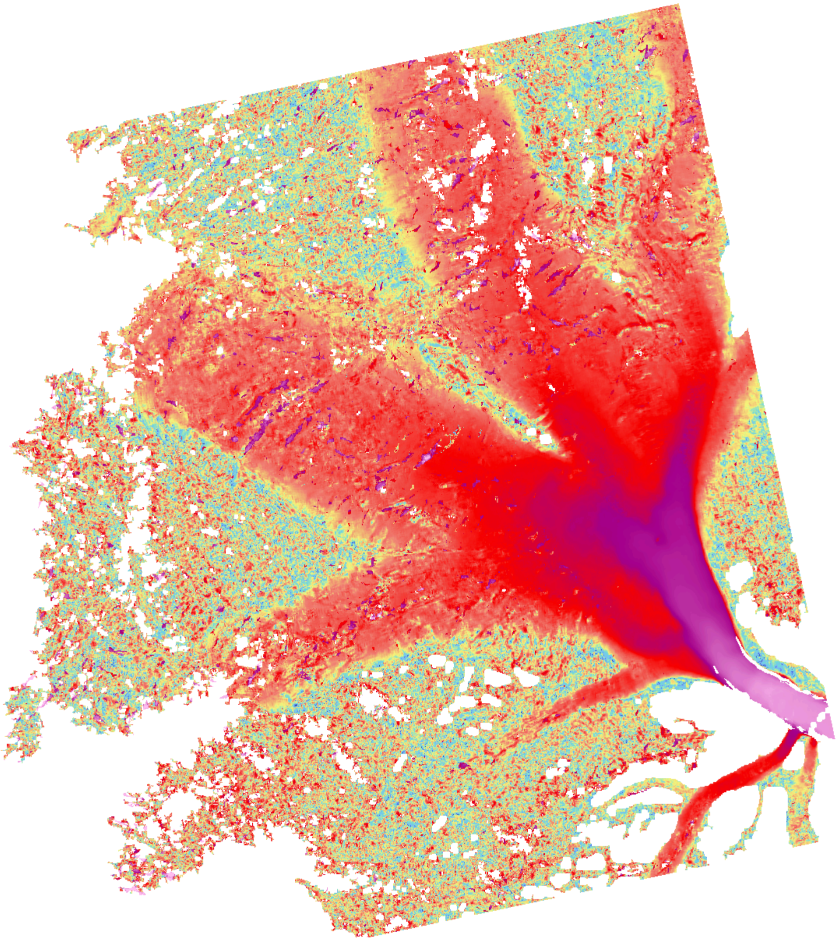

Figure 5.1: Optical Ice Velocity map of Kangerlussuaq Glacier generated using Sentinel-2 data.

Table 5.1: optical IV main data variables

Variable name	Variable description
land_ice_surface_northing_velocity	Ice velocity in true meters per day in the 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 the 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 (Sermeq Kujalleq), Upernavik, Petermann, Hagen, 79 fjord (Nioghalvfjerdsbræ) and Zachariæ (merged in a single product), Kangerlussuaq, Strorstrømmen and Helheim. Their location over the Greenland Ice Sheet is visualised in Figure 5.2.

Figure 5.2: Locations of the 9 large outlet glaciers for which optical IV products are available.

5.2 Product Data Format

The Ice Sheets CCI ice velocity products are distributed in a netCDF4 file. Figure 5.3 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 5.3: NetCDF file format used in IV products.

5.3 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

5.4 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].

5.5 Product Known Limitations

The applicability of offset tracking techniques is limited by the following factors:

- The temporal separation of the image acquisition pairs must be short enough for icesheet features to show little change in their appearance. This temporal separation is glacier and/or season dependent.
- Sun angle variations across the image. These variations reflect in solar illumination effects, which increase the noise in the imagery. A possibility for reducing this noise is to acquire imagery taken at the same time of day. The majority of this should be accounted for by the sun-synchronous orbit of Sentinel-2.
- Cloud coverage. The presence of clouds over ice and/or snow is one of the main sources of noise/failures for offset tracking-based algorithms. A possibility for reducing this noise is to apply a cloud mask before performing offset tracking.
- The presence of bed-related topographic features which remain stationary as the ice flows over them may distort the displacements measured.
- The motion of the ice-sheet features should be translational only.

5.6 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. Most GIS (Geographic Information System) software can be used to access the data products.QGIS is a good, free and open-source solution.

5.7 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.

6 Gravimetric Mass Balance

6.1 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. Further background is given by Barletta et al. (2013) and Döhne et al. (2023)

6.1.1 Mass change time series

The mass change time series contains the total 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 [RD2]). The total mass change of an ice sheet is the net balance between input (precipitations) and output (ice outflow, water runoff), and it is given in gigaton (Gt) which corresponds to a cubic kilometre of water, so to convert in (mean) sea level equivalent one need to divide the mass balance in Gt by the surface of the oceans in square kilometres.

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

6.1.2 Mass trend grids

For five-year periods grids of the trend in the derived GMB are also provided. This is given in units of mm water equivalent per year. This unit is a superficial density, and in order to retrieve the mass for each element, it has to be multiplied by the area of each element.

6.2 Product Data Format

The mass change time series (GISxx_grace.dat, where xx indicates the basin number with 00 being the 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 (CCI_GMB_GIS.nc) which contains this meta data (Table 6.1):

Table 6.1: CCI_GMB_GIS metadata

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.

Global Attribute Name	Data Type	Description
longitude_max	Float	Decimal degrees east, range -180 to +180.
time_coverage_start	String	Time of the first measurement in the data file in the form: “yyyymm”.
time_coverage_end	String	Time of the first measurement in the data file in the form: “yyyymm”.
time_resolution	String	5 year trends.
grid_projection	String	Geographical coordinates relative to WGS84
Units	String	Units used (mm water equivalent per year)

Variable attributes

Variable 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)

6.3 File naming conventions

The files for the mass changes time series are named GISxx_grace.dat, where xx indicates the basin number with 00 being the entire Greenland.

The files for the mass trend grids are named CCI_GMB_GIS.nc and collect all grids in a single netCDF file

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.

6.5 Product Known Limitation

The GMB has intrinsic low spatial resolution (about 250 km), so even if the gridded products are provided at higher resolution, the mass changes pattern seems more spread than what actually is. So comparison with products that have higher spatial resolution should be done using suitable filters.

6.6 Available Software Tools

The Ice Sheets CCI+ GMB 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).

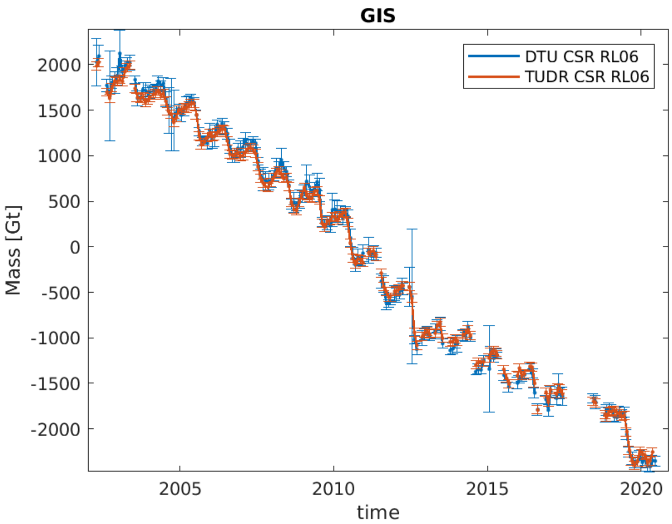

Figure 6.1: Example of total Greenland mass loss time series (basin 00 = GIS)

6.7 References

Barletta, V. R., Sørensen, L. S., & Forsberg, R. (2013). Scatter of mass changes estimates at basin scale for Greenland and Antarctica. The Cryosphere, 7(5), 1411-1432, doi:10.5194/tc-7-1411-2013

Döhne, T., Horwath, M., Groh, A., & Buchta, E. (2023). The sensitivity kernel perspective on GRACE mass change estimates. Journal of Geodesy, 97(1), 11, https://doi.org/10.1007/s00190-022-01697-8

7 Mass Flow Rate and Ice Discharge

7.1 Product Geophysical Data Content

This chapter describes the mass flow rate and ice discharge (MFID) product. The MFID product 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. The product utilises the information of flow and thickness changes from the ice velocity (IV) and surface elevation changes (SEC) ECVs. Figure 7.2 shows an example of the total mass flow rate and ice discharge from the Greenland Ice Sheet.

7.2 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 7.1 below. The first column, "Date", in YYYY-MM-DD format is the end of the month of the observation.

Figure 7.1: Greenland Ice Sheet sectors outlined and numbered (Zwally *et al.,* 2012), the purple dots indicate the location of the gates approximately 10 km from the ice margin in fast flowing areas.

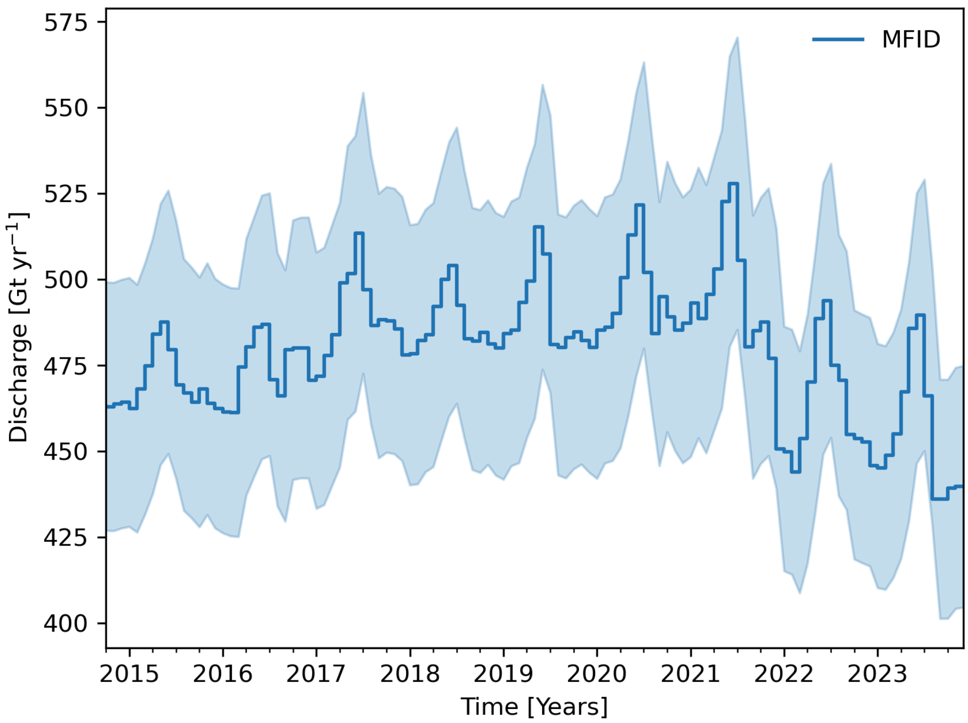

Figure 7.2: Mass Flux and Ice Discharge summed up for the Greenland Ice Sheet.

7.3 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].

7.4 Product Grid and Projection

There is no geospatial information for this product.

The product is organised by Zwally *et al.* (2012) sectors. The location of each sector is displayed in Figure 7.1.

7.5 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. The majority of the product uncertainty stems from the ice thickness, which is often not well known (Mankoff et al., 2020).

7.6 Available Software Tools

The products can be viewed by any software capable of reading comma delimited files. The above figure of the Greenland Ice Sheet time series can be generated in python using this script:

```
import pandas as pd
import matplotlib.pyplot as plt

# Create the figure and clear any existing plots
fig = plt.figure(1, figsize=(9, 5))  # width, height
fig.clf()

# Add a subplot
ax_D = fig.add_subplot(111)

# Read the data from CSV files
D = pd.read_csv("./out/GIS_D.csv", index_col=0, parse_dates=True)
err = pd.read_csv("./out/out_main/GIS_err.csv", index_col=0, parse_dates=True)

# Plot the data with step style
D.plot(ax=ax_D, drawstyle='steps', color='tab:blue', label='')

# Fill the area between the error margins
ax_D.fill_between(err.index,
            (D.values - err.values).flatten(),
            (D.values + err.values).flatten(),
            color='tab:blue', alpha=0.25, label='')

# Add legend and labels
ax_D.legend(["MFID"], framealpha=0)
ax_D.set_xlabel('Time [Years]')
ax_D.set_ylabel('Discharge [Gt yr$^{-1}$]')

# Save the figure
plt.savefig('MFID_GIS_D.png', transparent=False, dpi=300)
```

7.7 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

8 Supraglacial Lakes

8.1 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).

Supraglacial water bodies are estimated from Sentinel-2A/2B imagery, using a dual purpose deep-learning network for estimating the extent and depth of visible lake formations. These networks are trained on lake extent estimates from the method by Yang and Smith (2013) and Yang (2019), and lake depth estimates generated by DTU using their implementation of the Watta-algorithm.

The neural network emits two products, both in a natural 10 m X 10 m resolution:

- a segmentation raster of lake / no-lake.
- a depth-raster that is clipped to the lake extents of the segmentation mask, with 0 value assigned for no-lake conditions.

The outputs are by default in a GeoTiff raster format. The neural network model is not trained with bathymetric data beyond what overlaps with lakes, or tracks in close proximity of these, and the depth-estimates are therefore clipped to lake-extent. Outlines of lake extent are translated to shapefiles, while depth-estimates are given as rasters in a 10 m X 10 m pixel resolution (same as the S2 images).

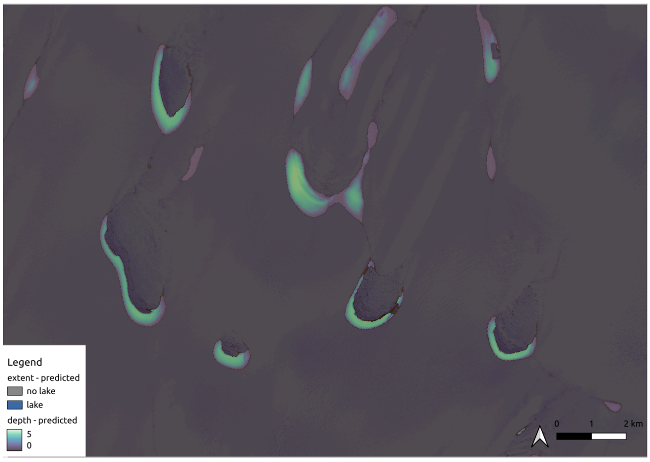

Figure 8.1a: SGL-depth predictions (superimposed on S2 input)

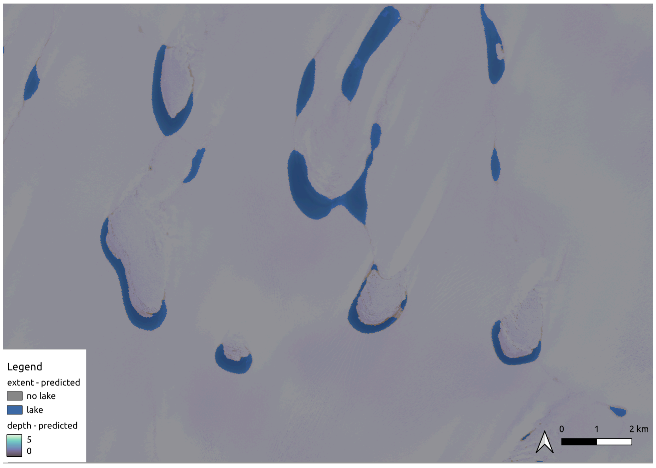

Figure 8.1 b: SGL extent-predictions (superimposed on S2 input)

8.2 Product Data Format

The following files are within each distributed product:

- A zip folder containing supraglacial lake extents for each time step in NetCDF format.
- A zip folder containing estimated supraglacial lake depth-rasters for each time step in NetCDF format.
- A combined NetCDF of all predicted supraglacial lake extents.
- A combined NetCDF containing all predicted supraglacial lake depths.

To reduce the size of individual products, the zip-files are partitioned based on S2 tiles, and the combined NetCDFs are merged based on glacier/catchments, SK or 79N.

Metadata for each product follows the specified CCI Data Standard, insofar as possible.

Table 8.1: Product Metadata for supraglacial lakes

Global attributes	
Attribute name	**Attribute description**
title	short description of dataset
institution	Where the data was produced, using names from CCI common vocabulary
source	original data source with DOI available. free-text, comma separated list.
history	processing history of dataset
references	references to algorithm, ATBD, technical note describing dataset.
tracking_id	UUID value
Conventions	The CF Version e.g. CF-1.8
product_version	product version of data file
format_version	CCI data format used, i.e. CCI Data Standards v2.3
Discovery Metadata	
Attribute name	**Attribute description**
summary	Describing the dataset, i.e. extent or depth data.
keywords	comma separated list of keywords and phrases.
id	-
naming authority	combination of naming authority and id should be a globally unique identifier for the dataset
keywords_vocabulary	if following a guideline for words/phrases in “keywords” attribute, describes guideline here
cdm_data_type	THREDDS data type appropriate for dataset (NetCDF 4)
comment	misc. information about dataset, if applicable
date_created	the date on which the data was created
creator_name	-
creator_url	-
creator_email	-
project	Climate Change Initiative - European Space Agency
geospatial_lat_min	decimal degrees north, range -90 to +90
geospatial_lat_max	decimal degrees north, range -90 to +90
geospatial_lon_min	decimal degrees east, range -180 to +180
geospatial_lon_max	decimal degrees east, range -180 to +180
geospatial_vertical_min	assumed to be metres above ground unless geospatial_vertical_units attribute defined
geospatial_vertical_max	assumed to be metres above ground unless geospatial_vertical_units attribute defined
time_coverage_start	format yyyymmddThhmmssZ
time_coverage_end	format yyyymmddThhmmssZ
time_coverage_duration	should be ISO8901 duration string
time_coverage_resolution	should be ISO8901 duration string
standard_name_vocabulary	name of controlled vocabulary from which variable standard names are taken e.g. CF Standard Name Table v77
licence	describe restrictions to data access and distributions
CCI project specific	
Attribute name	**Attribute description**

platform	Satellite name. use names from CCI common vocabulary list. Separated by commas if more than one
sensor	Sensor name, use names from CCI common vocabulary. Separated by commas if more than one
spatial_resolution	free-text string describing approximate resolution of product, e.g. “1.1km at nadir”. Intended to provide a useful indication to the user, so if more than one resolution is relevant e.g. grid resolution and data resolution, then both can be included
key_variables	comma separated list of the key primary variables in the file. i.e. those that have been scientifically validated, and are appropriate for display in the CCI Open Data Portal and CCI Toolbox. These should be identified using the variable id’s in the file
Gridded L3 / L4 data on regular lat/lon grid	
Attribute name	**Attribute description**
geospatial_lat_units	-
geospatial_lon_units	-
geospatial_lon_resolution	-
geospatial_lat_resolution	-

8.3 File naming convention

Extents of lakes is given by `ESACCI-GIS-L4-LK_PRODUCTS-SGL-EXTENT_<S2TILE>-<YYYYMMDD>-fv<File Version>.nc`

Depth of lakes is named by `ESACCI-GIS-L4-LK_PRODUCTS-SGL-DEPTH_<S2TILE>-<YYYYMMDD>-fv<File Version>.nc`

Where `S2TILE` reflects the tile over which the product is generated, and `YYYYMMDD` denotes year, month, and day, respectively.

8.4 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] (EPSG:3413). The product is generated in the same projection as the S2 input used to generate it, and subsequently reprojected to EPSG:3413.

8.5 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 in the training data 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 thresholds then the upper extent is retained, which will best compensate for ice-covered lakes and lakes with accumulated sediment at the bottom, as well as reduce the probability of false matches in regions of saturated snow.

The neural network being trained to yield similar labels as the training data should, insofar as possible, demonstrate similar properties when dealing with limitations of water body detection. This will be reflected in the validation scores (F1 or Dice coefficient) of how well the network fits the validation data. The ability of the model to extrapolate beyond the domain of the training data is also untested and presumed limited.

8.6 Available Software Tools

The SGL product is distributed as NetCDF, which is a standard ESRI file format for storing multidimensional scientific data. The data format is readable by most open source (e.g. QGIS: www.qgis.org) or commercial GIS software (e.g. ArcGIS).
(ref: https://pro.arcgis.com/en/pro-app/latest/help/data/multidimensional/what-is-netcdf-data.htm)

8.7 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.

9 Calving Front Locations (not in production)

9.1 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 9.1). The format is standard GeoJSON in latitude and longitude (WGS84) projection. The main attributes are shown in Section 9.2. The basic data are vector line files (not polygons).

Figure 9.1: 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.

9.1.1 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 9.1.

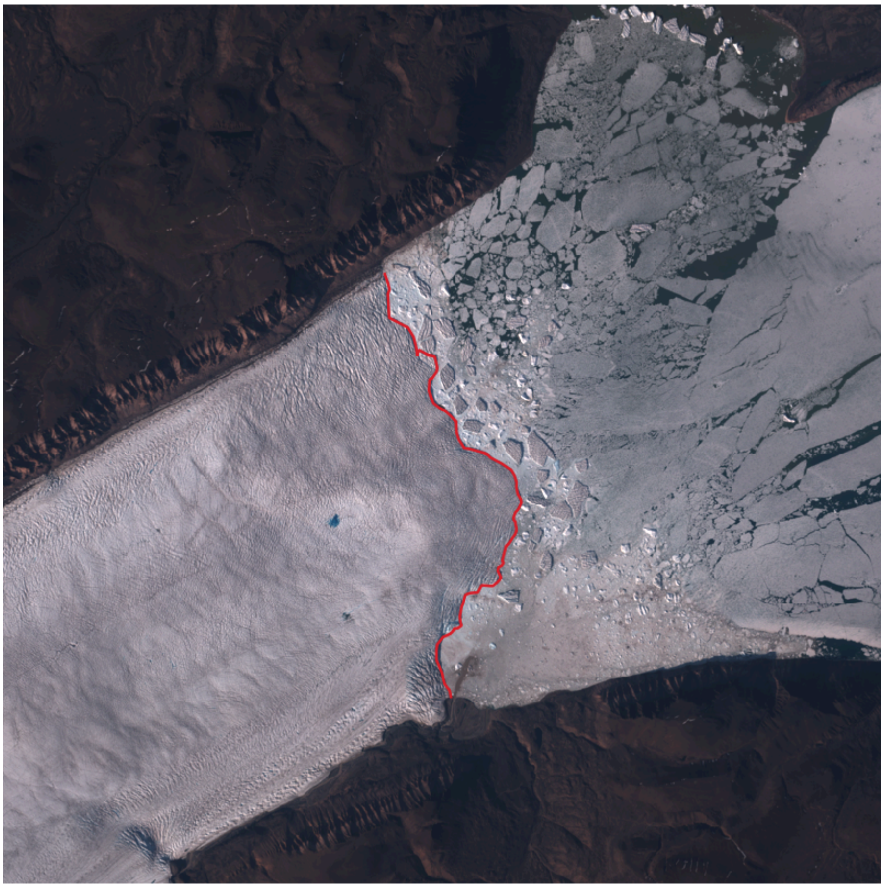

Figure 9.2: Example CFL of the Hagen glacier.

9.1.2 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.

9.2 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 9.1).

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 9.1 presents the CFL product structure.

Table 9.1: 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

9.3 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 9.2: 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

9.4 Product Grid and Projection

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

9.5 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].

9.6 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).

10 Experimental Ice Uplift/Subsidence from InSAR Line-of-sight velocity

10.1 Product Geophysical Data Content

The Line-of-sight Ice Velocity product (LoS-IV) is a prototype product containing time series of single-pair Sentinel-1 InSAR displacement measurements. The aim of this product is to provide a product with high temporal resolution tailored to study rapidly varying and transient ice uplift/subsidence phenomena, such as those associated with subglacial water transport. Observing such phenomena on the ice cap is challenging, as the InSAR method is sensitive only to displacements in the radar line-of-sight direction, and these contain contributions from both horizontal ice flow and subsidence/uplift of the ice surface, with the horizontal flow contribution typically being much larger, and the subsidence/uplift typically appearing only sporadically and on a much smaller spatial scale. With careful interpretation, however, the product can be used for tracing subglacial water propagation pathways (by assuming the subsidence/uplift is caused by subglacial water displacing the ice surface), and, in some cases, quantify the amount of water propagating (Andersen et al., 2023). Despite its name, the LoS-IV product actually provides a time series of vertical displacement estimates (uplift/subsidence), derived from the InSAR LoS displacement under the assumption of stable horizontal ice flow. The product contains all information necessary to easily convert the provided uplift estimate back to LoS velocity, which could be relevant, for example, if multiple products acquired from different tracks were combined to derive both horizontal flow and vertical displacement as in (Maier et al., 2023). To support such calculations, also the line-of-sight vector elevation and azimuth angles are provided in the product.

The main measurement provided in the NetCDF file is a time series of vertical displacement estimates, derived from multiple DInSAR observations from a single Sentinel-1 track in the following way:

For each InSAR pair, generated from acquisitions typically 6 days apart, a line-of-sight velocity map is first generated by unwrapping, calibrating and geocoding the interferogram, converting the measured displacement to velocity by dividing with the temporal separation between the two acquisitions in the InSAR pair. Once the entire time series has been generated, the pixelwise median LoS-velocity is calculated and subtracted from the individual velocity maps. The purpose of this is to remove the bulk of the horizontal ice flow velocity contribution to the LoS velocity, making observation of small-scale uplift/subsidence phenomena easier. This means, however, that variations in the horizontal flow velocity (which can be correlated with the transients) will still be visible in the data. They tend however, to be much more spatially correlated than the uplift/subsidence phenomena. Following this, the LoS velocity anomaly is converted to a displacement by multiplying with the temporal separation for each interferogram. Finally, under the assumption that the residual signal is purely due to vertical displacement, Line-of-sight displacement anomaly is converted to vertical displacement to produce the output variable, called uplift.

The uplift time series variable provided in the NetCDF should be interpreted in the following way:

For a given timestamp, the uplift is the change in the ice surface height (positive for uplift, negative for subsidence) between the two acquisitions used generate the DInSAR displacement map, under the assumption that horizontal flow speed changes over the duration of the timeseries are negligible. The dates of the two acquisitions are available in the time_bnds variable, whereas the time variable represents the midpoint time of the two acquisitions. An example of an uplift map from the prototype product is shown in Figure 10.1.

To convert from estimated uplift back to InSAR-measured line-of-sight velocity, the auxiliary variables in the NetCDF, los_elevation_angle, los_velocity_time_median and TB can be used together with the uplift variable, as:

v_los [m/d]= los_velocity_time_median + uplift*sin(los_elevation_angle)/TB

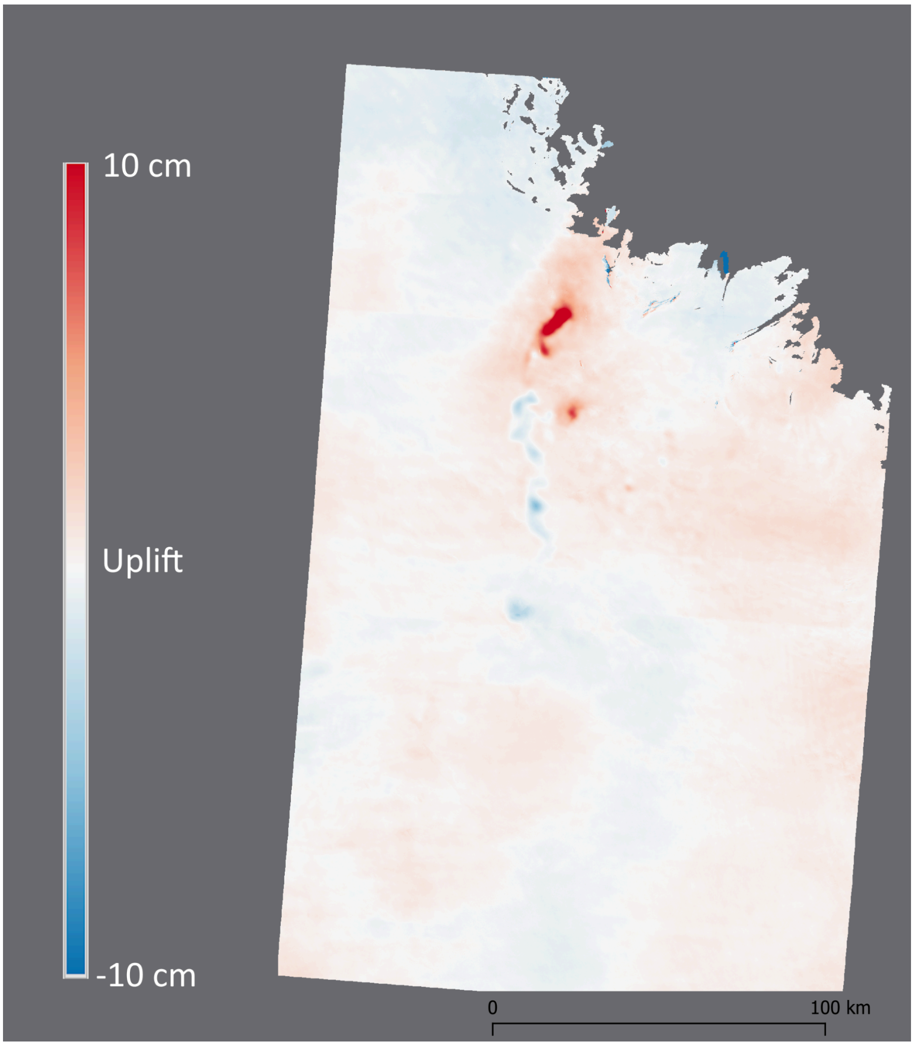

Figure 10.1 Example uplift map (single timestep 2020-08-03) from the NEGIS prototype product. Water propagating from South to North pushes up the ice surface (red), leaving a trail of subsidence(blue), where the water has passed through. The map represents the estimated change in surface height from 2020-02-28 to 2020-03-06.

10.2 Product Data Format

The product is provided in a NetCDF4-Classic file using CF-metadata conventions for easy ingestion into tools like QGIS, with the variables described in Table 10.1

Table 10.1: Product nomenclature

Variable	Type	Units	Axes	Description
`crs`	string	N/A	N/A	Attributes of this variable describe the coordinate reference system, as per the CF Metadata convention
`time`	float64	days	time	Midpoint time of InSAR pair used for each map, measured in days since 1990-1-1 0:0:0

x	float64	m	x	x coordinate of projection
y	float64	m	y	y coordinate of projection
time_bnds	float64	days	time,2	First and last date of InSAR pair used for each map, measured in days since 1990-1-1 0:0:0
TB	float64	days	time	Temporal baseline of InSAR pair used for each map (i.e. time between first and last acquisition)
los_azimuth_angle	float32	radians	y, x	Line-of-sight azimuth angle from local East (increasing anti-clockwise, i.e. E=0, N=pi/2)
los_elevation_angle	float32	radíans	y,x	Line-of-sight elevation angle, positive from local level towards sensor
uplift	float32	m	time,y,x	Inferred vertical displacement derived from line-of-sight displacement, (positive up)
los_velocity_time_median	float32	m/day	y,x	Pixelwise time median of original line-of-sight velocity measurements.

10.3 File naming convention

The NetCDF files are named in the following way:

`greenland_uplift_s1_<region>_t<track><pass>_<date1>_<date2>.nc`

where

- `region` is a descriptive name of the region covered by the data
- `track` is the Sentinel-1 track number (i.e. relative orbit) from which the data were acquired
- `pass` is a single lowercase ‘a’ or ‘d’ indicating whether the S1 data were acquired from an ascending (‘a’) or descending (‘d’) pass
- `<date1>` and `<date2>` are the dates of the first and last uplift maps in the timeseries in the format YYYYMMDD

Example (the name of the prototype product):

`greenland_uplift_s1_negis_t112d_20200112_20201225.nc`

This name indicates data from the North East Greenland Ice Stream (NEGIS) acquired from track 112 (descending) with the timeseries starting at 2020-01-12 and ending 2020-12-25.

10.4 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].

10.5 Product Known Limitations

Being a prototype product, careful interpretation is required to use these data, as many spurious signals are present in the data.

1) Unwrapping errors occur when the interferometric phase unwrapping adds an incorrect number of phase cycles to the interferometric phase across a region in the image. These errors typically result in unphysical, sharply delineated regions of bias compared to the surroundings, as illustrated in Fig. 10.2, and no measurements in such regions should be trusted.

2) Atmospheric artefacts can arise from both ionospheric scintillations, and from variations in the tropospheric water content affecting the radar signal propagation. They are typically correlated on a much larger spatial scale than the localised uplift/subsidence signals. Sometimes, the atmospheric signal arises from propagation conditions in a single image, and when this image is used in two subsequent InSAR pairs (i.e., as the first image in one interferogram and as the last image in the subsequent interferogram), the atmospheric signal reverses sign between the two resulting displacement maps.

3) All DInSAR measurements are calibrated using ground control points (GCPs) of assumed known velocity. This is done for each displacement map by fitting a plane to the observed velocity differences (measured minus known GCP velocity) and subtracting the plane fit from the displacement map. GCPs are placed across the image in slow-moving regions, i.e. outside of ice streams and glaciers, where the velocity variations are assumed negligible. Atmospheric propagation variations can, however, due to their large spatial correlation, introduce errors at many GCPs, resulting in calibration errors. These kinds of errors exhibit a bilinear variation across the image, i.e. a "tilt" of the displacement map.

4) Horizontal flow changes. Although the uplift estimate provided in this product is generated by assuming negligible horizontal flow changes, such changes do occur, especially in faster flowing regions like ice streams and glaciers, and the error pattern

If trying to quantify observed uplift/subsidence events, the biases introduced by the error sources described above should be accounted for, e.g. by estimating the bias in a region surrounding the uplift event.

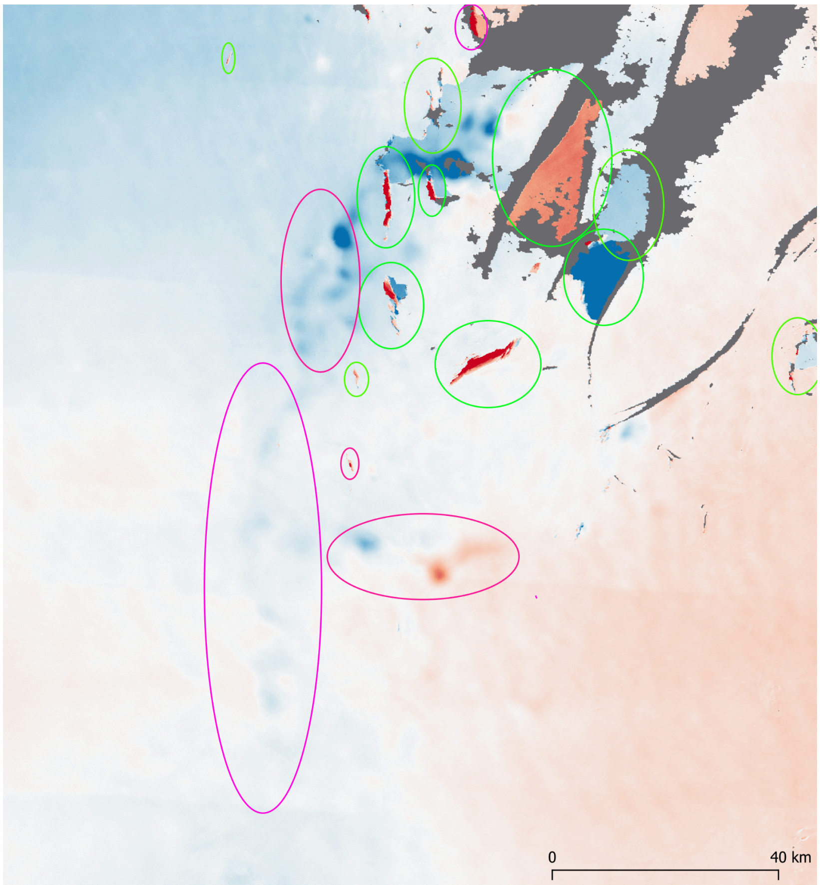

Figure 10.2 Uplift map with examples of typical signals and errors. The areas in the magenta ellipses represent real geophysical signals, whereas areas in green ellipses contain phase unwrapping artefacts, characterised by a sharp delineation to the surroundings.. The linear gradient from the top-left to the bottom right corner is typically the result of a calibration error, and likely not caused by surface displacement.

10.6 Available Software Tools

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. Most GIS (Geographic Information System) software can be used to access the data products. QGIS is a good, free and open-source solution. To view the uplift timeseries, the QGIS plugin "Raster Timeseries Manager '' can be installed.

10.7 References

Andersen, J. K., Rathmann, N., Hvidberg, C. S., Grinsted, A., Kusk, A., Merryman Boncori, J. P., & Mouginot, J. (2023). Episodic subglacial drainage cascades below the Northeast Greenland Ice Stream. Geophysical Research Letters, 50, e2023GL103240. https://doi.org/10.1029/2023GL103240

Maier, N., Andersen, J. K., Mouginot, J., Gimbert, F., & Gagliardini, O. (2023). Wintertime supraglacial lake drainage cascade triggers large-scale ice flow response in Greenland. Geophysical Research Letters, 50, e2022GL102251. https://doi.org/10.1029/2022GL102251