ESA Climate Change Initiative (CCI+)

Essential Climate Variable (ECV)

Antarctica_Ice_Sheet_cci+ (AIS_cci+)

D4.2 Product User Guide (PUG)

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1. Signatures page

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2. Change Log

Issue	Author	Affected Section	Change	Status
0.5	D. Fantin	All	Document Creation	
1.0	M. Horwath	All	Document consolidation for delivery	Delivered to ESA
1.1	D. Fantin	6.1	Comments addressed	Delivered to ESA

3. Acronyms and Abbreviations

Acronym	Explanation
AIS	Antarctic Ice Sheet
ADP	Algorithm Development Plan
AIS_cci+	Antarctic Ice Sheets CCI project Extension
API	Antarctic Peninsula
ATBD	Algorithm Theoretical Basis Document
CAR	Climate Assessment Report
CCI(+)	Climate Change Initiative (Extension)
CFL	Calving Front Location
CONAE	Comisión Nacional de Actividades Espaciales
DEM	Digital Elevation Model
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DTU	Danish Technical University
EAIS	East Antarctic Ice Sheet
ECV	Essential Climate Variable
ENVEO	ENVironmental Earth Observation GmbH
EO	Earth Observation
ESA	European Space Agency
GLL	Grounding Line Location
GLM	Grounding Line Migration
GMB	Gravimetric Mass Balance
ISCL	Ice Shelf Coast Line
IV	Ice Velocity
IV-TDM	Ice Velocity Tidal Correction Module
IVC	Ice Velocity Change
MFID	Mass Flux Ice Discharge
MPC	Mission Performance Cluster
SEC	Surface Elevation Change
SL	Science Lead
SOW	Statement of Work
ST	Science & Technology AS
TOPS	Terrain Observation by Progressive Scans
TUD	Technical University of Dresden
UB	University of Bristol
UCL	University College London
UL	University of Leeds
UN	University of Northumbria
WAIS	West Antarctic Ice Sheet

NASA	National Aeronautics and Space Administration
SAR	Synthetic Aperture Radar
InSAR	Interferometric SAR
ML	Machine Learning

1 Introduction

1.1 Purpose and Scope

This document contains the Product User Guide (PUG) for the Antarctica_Ice_Sheet_cci (AIS_cci) project for CCI+ Phase 2, in accordance with contract and SoW [AD1 and AD2].

The document aims to describe the AIS_cci data products to the end user. The document provides information about:

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

1.2 Document Structure

This document is structured as follows:

- Chapter 1 is this chapter.
- Chapter 2 describes the Surface Elevation Change (SEC) ECV parameter.
- Chapter 3 describes the Ice Velocity (IV) ECV parameter.
- Chapter 4 describes the Grounding Line Location (GLL) ECV parameter.
- Chapter 5 describes the Gravimetric Mass Balance (GMB) ECV parameter.
- Chapter 6 describes the Ice Shelf CoastLine (ISCL) ECV parameter
- Chapter 7 describes how to access and download the data products.
- Chapter 8 describes how to Obtain the Data Products.

1.3 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	ESA/Contract No. 4000143397/23/I-NB CCI+ PHASE 2 - AIS	CCI+ PHASE 2 - NEW R&D ON CCI ECVS for AIS CCI	13.02.2024	NA
AD2	ESA-EOP-SC-AMT-2023-12 and its appendix 2	STATEMENT OF WORK, ESA EXPRESS PROCUREMENT – EXPRO CCI+ Phase 2 – Theme II – Antarctic Ice Sheet (AIS)	14.07.2023	1.2

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

2 Surface Elevation Change (SEC) Products

This chapter describes the Surface Elevation Change ECV parameter products.

In Phase 2 of the project we have continued the production of SEC products from satellite radar altimetry and updated our product to use the latest fully reprocessed and validated baseline archive of operational Level-2 products from ESA for ERS-1, ERS-2 and Envisat, and new Thematic products for CryoSat-2 and Sentinel-3. Additionally, we also use Level-2 products from the laser altimetry mission ICESat-2 to produce SEC over the period 2018 to 2024. Finally, we produce gridded annual height changes (dh) for the full radar altimeter record.

2.1 Product Geophysical Data Content

This data set provides surface elevation change (SEC) and the associated uncertainty for the Antarctic Ice sheet derived from ERS-1, ERS-2, Envisat, CryoSat-2, Sentinel-3A and Sentinel-3B radar altimetry, and from ICESat-2 laser altimetry processed from the following ESA and NASA products:

Altimetry Mission	Source Altimetry Products
ERS-1 (1991-1996)	ESA FDR4ALT LI v1
ERS-2 (1995-2003)	ESA FDR4ALT LI v1
Envisat (2002-2012)	ESA FDR4ALT LI v1
CryoSat-2 (2010-..)	ESA CryoTEMPO C001
Sentinel-3A (2016-..)	ESA Thematic LI BC05
Sentinel-3B (2018-..)	ESA Thematic LI BC05
ICESat-2 (2018-...)	NASA ATL06, version 006

Surface elevation change products are calculated on a 5km polar stereo grid over 5 years periods between 1991 and 2021, starting from when ERS-1 became operational in August 1991, and then incorporating cross-calibrated data from new missions as they became available. Additionally, SEC products are separately processed over each mission's operational lifetime.

The algorithm used to calculate SEC in this data set is the surface plane fit method (McMillan et al, 2014). In this method, all local radar altimetry measurements of elevation and backscattered power in a grid cell are fitted to a surface model which separates out the contributions from the topography, radar penetration, the imaging geometry, and the temporal change. This algorithm can be applied to all recent radar altimetry missions, including CryoSat-2, whose orbit does not repeat within a typical 30-day measurement period, and when in SAR interferometric mode over the Antarctic margins locates the true measurement locations which are irregularly dispersed over complex sloping terrain. To derive SEC from ICESat-2 laser altimetry data, the plane fit method is also used, with adjusted parameters to account for the different temporal and spatial sampling of ICESat-2. The full details of the laser altimetry data processing are described in Ravinder et al (2024).

A GIA (glacial isostatic adjustment) correction is applied using the *IJ05* model [Ivins and James, 2005]

In addition, products include matching grids of IMBIE glaciological basin id numbers (Zwally et al , 2012) and surface types from BedMachine v2.

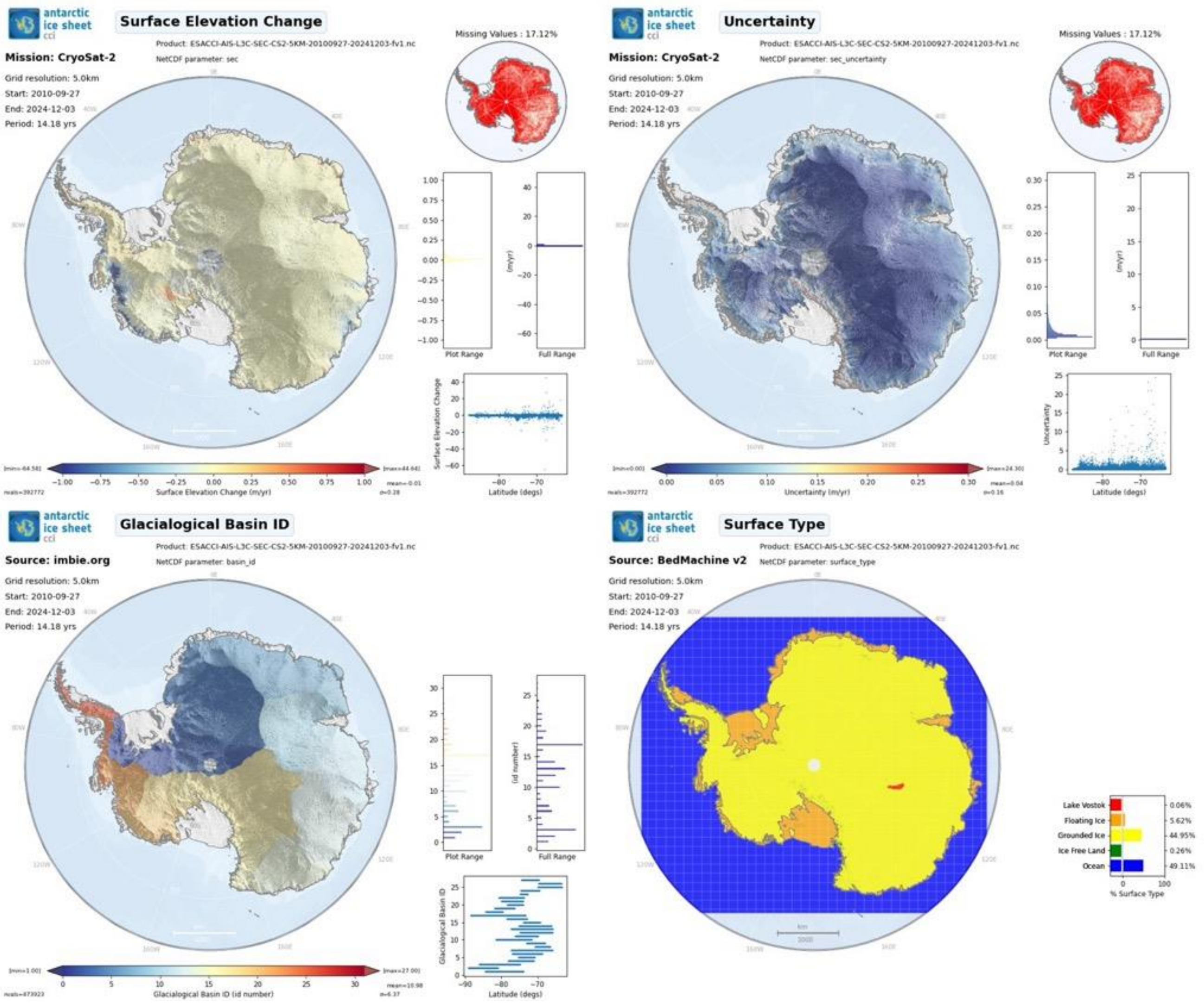


Figure 2-1: Quicklook Images of SEC Product Parameters (Example from CryoSat-2 Single Mission Product).

2.2 Product Data Format

All SEC data products are in NetCDF v4 classic format , and are accompanied by quicklook images (Figure 2-1) of each main parameter in PNG format. Data products are CF1.8 compliant (https://cfconventions.org) and follow CCI Data Standards v2.2.

The SEC data product produced from ICESat-2 follows a similar format and is accompanied by similar quicklook images (Figure 2-2).

Each SEC product is packaged as a compressed zip file containing a NetCDF data product and associated quicklook images.

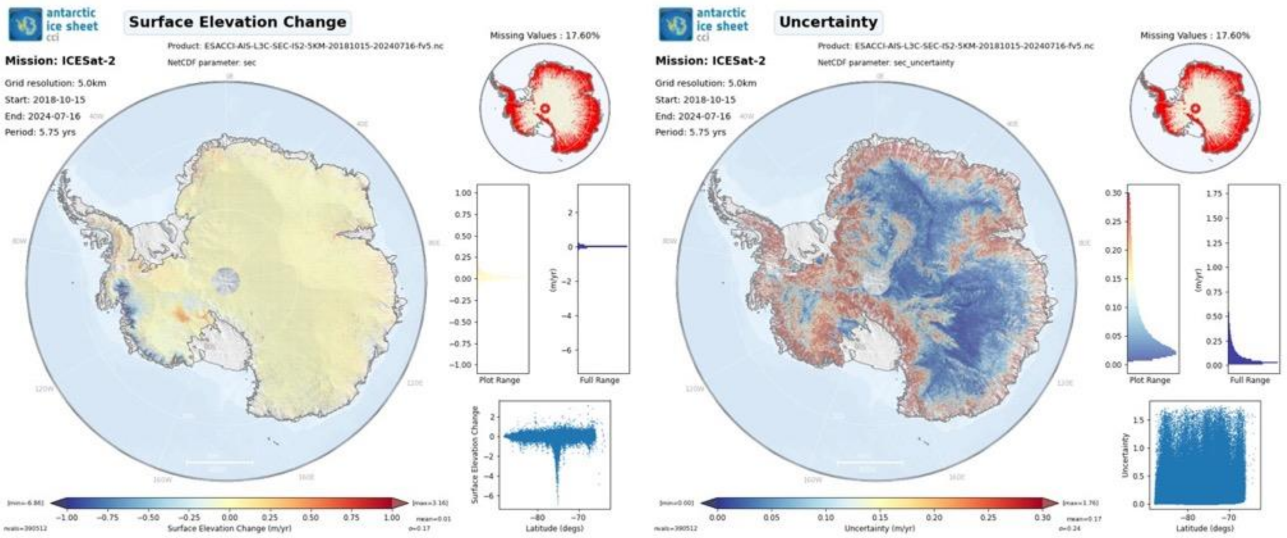


Figure 2-2: Quicklook Images of ICESat-2 SEC Product Parameters.

2.3 File naming convention

File naming conventions for SEC products are as follows:

Single Mission Product File Naming

For single mission SEC products, the file name stem of each package, NetCDF file or quick look image file is:

ESACCI-AIS-L3C-SEC-<Mission>-<Grid Resolution>KM-<Start Date>-<End Date>-fv<File Version>, where

File Name String	Description	Example Values
<Mission>	Mission identifier (3-chars)	IS2, S3B, S3A, CS2, ENV, ER2, ER1
<Grid Resolution>	Grid resolution in km	5
<Start Date>	First date of epoch used to calculate SEC as YYYYMMDD	20100927
<End Date>	End date of epoch used to calculate SEC as YYYYMMDD	20241231
<File Version>	Version of this file. The first version is 1	1

Each file ends in either .nc (NetCDF files), .png (quicklook images), or .zip (packages).

Quicklook images of each main parameter in a product are named <Main File Name>_<parameter>.png:

Quicklook Name	Parameter Shown
<ESACCI-…..>_sec.png	Surface Elevation Change (SEC)
<ESACCI-…..>_sec_uncertainty.png	Uncertainty (error) in SEC
<ESACCI-…..>_basin_id.png	IMBIE glaciological basin id numbers
<ESACCI-…..>_surface_type.png	Surface type from BedMachine v2

An example of file naming for the CryoSat-2 single mission product:

Package Name	ESACCI-AIS-L3C-SEC-CS2-5KM-20100927-20210202-fv1.zip (contains the files below)
Netcdf Name	ESACCI-AIS-L3C-SEC-CS2-5KM-20100927-20241231-fv1.nc
Quicklook images	ESACCI-AIS-L3C-SEC-CS2-5KM-20100927-20241231-fv1_sec.png ESACCI-AIS-L3C-SEC-CS2-5KM-20100927-20241231-fv1_sec_uncertainty.png ESACCI-AIS-L3C-SEC-CS2-5KM-20100927-20241231-fv1_basin_id.png ESACCI-AIS-L3C-SEC-CS2-5KM-20100927-20241231-fv1_surface_type.png

Multi-Mission 5-year Mean Product File Naming

For multi-mission 5-year Mean SEC products the file name stem of the package, and nectdf and quicklook files is:

ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-<Start Date>-<End Date>-fv<File Version>, where

Name Section	Description	Example Values
<Start Date>	Year used to calculate the first 5-year period as YYYY or for quicklooks it is the first year of the 5-year period of the quicklook.	1991 (note that the NetCDF file contains grids of every 5-year period from 1991 onwards, stepped by 1-year)
<End Date>	End year used to calculate last 5-year period as YYYY or for quicklooks it is the last year of the 5-year period of the quicklook.	2024
<File Version>	Version of this exact file. The first version is 1	1

Each file ends in either .nc (NetCDF files), .png (quicklook images), or .zip (packages).

Quicklook images of each main parameter in a product are named <Main File Name>_<parameter>.png:

Quicklook Name	Parameter Shown
<ESACCI-.....>_sec.png	Surface Elevation Change (SEC)
<ESACCI-.....>_sec_uncertainty.png	Uncertainty (error) in SEC
<ESACCI-.....>_basin_id.png	IMBIE glaciological basin id numbers
<ESACCI-.....>_surface_type.png	Surface type from BedMachine v2

An example of file naming for the 5-year mean multi-mission product:

Package Name	ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-1991-2024-fv1.zip (contains the files below)
Netcdf Name	ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-1991-2024-fv1.nc (contains grids of SEC for every 5-year period between 1991 and 2024, stepped by 1 month)
Quicklook images	ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-199101-199601-fv1_sec.png ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-199101-199601-fv1_sec_uncertainty.png ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-199101-199601-fv1_basin_id.png ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-199101-199601-fv1_surface_type.png … (stepped by 1 month)… ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-201912-202412-fv1_sec.png ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-201912-202412-fv1_sec_uncertainty.png ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-201912-202412-fv1_basin_id.png ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-201912-202412-fv1_surface_type.png

File naming conventions for the annual dh product are similar to the ones used for the SEC products. For annual dh product, the file name stem of the package, and nectdf and quicklook files is:

ESACCI-AIS-L3C-dh-MULTIMISSION-5KM-MEANS-<Year>-fv<File Version>, where

Name Section	Description	Example Values
<Year>	Year in which mean dh value is calculated as YYYY	2024
<File Version>	Version of this exact file. The first version is 1	1

Each file ends in either .nc (NetCDF files), .png (quicklook images), or .zip (packages).

Quicklook images of each main parameter in a product are named <Main File Name>_<parameter>.png:

Quicklook Name	Parameter Shown
<ESACCI-…..>_dh.png	Surface Elevation Change (SEC)
<ESACCI-…..>_dh_uncertainty.png	Uncertainty (error) in SEC

2.4 Product Grid and Projection

The SEC and annual dh netCDF products are gridded at 5km spacing on a south polar stereographic projection. The projection and grid specifications are shown here (and also contained within each netCDF file):

Projection parameter	Value
Projection Name	Polar Stereographic
Projection Coordinate Reference System (CRS)	3031
Ellipsoid	WGS84
Latitude of Origin	-71N
Central Meridian	0W

Grid parameters	Value
Minimum Cartesian x-coordinate - easting, of centre of each grid cell	-2817500. (m)
Minimum Cartesian y-coordinate - northing, of centre of each grid cell	-2417500. (m)
Grid bin size	5000 (m)
Number of grid points in x-direction	1128
Number of grid points in y-direction	968

2.5 Metadata Information Sheet

The following is the netCDF CDL (ie the list of parameters and attributes) of a multi-mission SEC product:

netcdf ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-1991-2024-fv1 {
dimensions:

```
    ny = 968 ;
    nx = 1128 ;
    time_period = 360;

variables:

    float sec(time_period, ny, nx) ;
        sec:long_name = "surface elevation change" ;
        sec:units = "m/yr" ;
        sec:source = "multi-mission radar altimetry, ERS-1 FDR4ALT v1,  ERS-2 FDR4ALT v1, ENVISAT FDR4ALT v1, CryoSat-2 CryoTEMPO C001 S3-A
        Thematic LI BC05, S3-B Thematic LI BC05" ;
        sec:grid_mapping = "grid_projection" ;

    float sec_uncertainty(time_period, ny, nx) ;
        sec_uncertainty:long_name = "uncertainty in surface elevation change" ;
        sec_uncertainty:units = "m/yr" ;
        sec_uncertainty:grid_mapping = "grid_projection";

    float x(nx) ;
        x:long_name = "Cartesian x-coordinate - easting, of centre of each grid cell" ;
        x:units = "meters" ;
        x:standard_name = "projection_x_coordinate" ;
        x:min_val = -2817500. ;
        x:binsize = 5000. ;

    float y(ny) ;
        y:long_name = "Cartesian y-coordinate - northing, of centre of each grid cell" ;
        y:units = "meters" ;
        y:standard_name = "projection_y_coordinate" ;
        y:min_val = -2417500. ;
        y:binsize = 5000. ;

    char grid_projection ;
        grid_projection:ellipsoid = "WGS84" ;
        grid_projection:crs = "epsg:3031" ;
        grid_projection:latitude_of_origin = -71. ;
        grid_projection:grid_mapping_name = "polar_stereographic" ;
        grid_projection:false_easting = 0. ;
        grid_projection:false_northing = 0. ;
        grid_projection:central_meridian = 0. ;

    double lat(ny, nx) ;
        lat:units = "degrees_north" ;
        lat:standard_name = "latitude" ;
        lat:long_name = "latitude coordinate" ;
        lat:min_val = -89.9674601532943 ;
        lat:max_val = -56.7587107166777 ;
    double lon(ny, nx) ;
        lon:units = "degrees_east" ;
        lon:standard_name = "longitude" ;
        lon:long_name = "longitude coordinate" ;
        lon:min_val = 0.0592510435250638 ;
        lon:max_val = 359.940748956475 ;

    byte surface_type(ny, nx) ;
        surface_type:_FillValue = -128b ;
        surface_type:coordinates = "lon lat" ;
        surface_type:long_name = "surface type from mask" ;
        surface_type:flag_values = 0b, 1b, 2b, 3b, 4b ;
        surface_type:flag_meanings = "ocean ice_free_land grounded_ice floating_ice lake_vostok" ;
        surface_type:source = https://nsidc.org/data/nsidc-0756/versions/2;
        surface_type:valid_min = 0b ;
        surface_type:valid_max = 4b ;
```

surface_type:comment = "Surface type identifier, for use in discriminating different surfaces types within the SEC grid; derived from the BedMachine Antarctica version 2 (Morlighem, 2020) datasets." ;

byte **basin_id**(ny, nx) ;
basin_id:_FillValue = -128b ;
basin_id:coordinates = "lon lat" ;
basin_id:long_name = "Glacialogical basin identification number" ;
basin_id:comment = "IMBIE glacialogical basin id number (Zwally et al., 2012) associated with each measurement. Values are : 0 (outside mask), 1-27 (basin values for Antarctica)" ;
basin_id:source = "IMBIE http://imbie.org/imbie-2016/drainage-basins/" ;

float **start_time**(time_period) ;
start_time:comment = "the start time of the 5yr time slice period used to calculate surface elevation change, in decimal years and months" ;
start_time:long_name = "start time" ;
start_time:units = "years followed by month" ;

float **end_time**(time_period) ;
end_time:comment = "the end time of the 5yr time slice period used to calculate surface elevation change, in decimal years and months" ;
end_time:long_name = "end time" ;
end_time:units = "years" ;

float **cell_time_lengths**(time_period, ny, nx) ;
cell_time_lengths:_FillValue = NaNf ;
cell_time_lengths:comment = "for each time slice, the length of time (in years) between first and last datapoints in each grid cell, used for surface elevation change calculation" ;
cell_time_lengths:long_name = "period covered by grid cell" ;
cell_time_lengths:units = "years" ;
cell_time_lengths:min_val = 2.53185118646605 ;
cell_time_lengths:max_val = 4.98137210869077 ;

float **cell_start_times**(time_period, ny, nx) ;
cell_start_times:_FillValue = NaNf ;
cell_start_times:comment = "for each 5yr time slice, the time of the first datapoint in each grid cell period, in years since 1991.0" ;
cell_start_times:long_name = "first time in grid cell" ;
cell_start_times:units = "years" ;
cell_start_times:min_val = 0.5753424657534246 ;
cell_start_times:max_val = 30.923287671232877 ;
float **cell_end_times**(time_period, ny, nx) ;
cell_end_times:_FillValue = NaNf ;
cell_end_times:comment = "for each 5yr time slice, the time of the last datapoint in each grid cell period, in years since 1991.0" ;
cell_end_times:long_name = "last time in grid cell" ;
cell_end_times:units = "years" ;
cell_end_times:min_val = 4.791780821917808 ;
cell_end_times:max_val = 33.9617523766749 ;

// global attributes:
:**title** = "5yr Antarctic Surface Elevation Change at 5.0km resolution from 1991 to 2025 from Multi-Mission Radar Altimetry" ;
:**institution** = "University College London (UCL)" ;
:**creator_email** = "cpom@leeds.ac.uk" ;
:**creator_name** = "University College London (UCL), Centre for Polar Observation and Modelling (CPOM)" ;
:**creator_url** = "www.cpom.ucl.ac.uk/csopr" ;
:**comment** = "This data was prepared by UCL as a part of the ESA Antarctic CCI+ project" ;
:**references** = "Trends in Antarctic Ice Sheet Elevation and Mass, Shepherd et al, GRL,2019,doi: 10.1029/2019GL082182" ;
:**source** = "ERS-1 REAPER v1, ERS-2 REAPER v1, ENVISAT GDRv3, CryoSat-2 Baseline-D L2i, S3-A PB2.68, S3-B PB2.68" ;
:**history** = "2025-05-25T22:46:27Z - Product generated by CPOM Software Processor, commit 0ded87aa6" ;
:**tracking_id** = "a8ac616a-bda2-11eb-8fd8-e35b9066c711" ;
:**Conventions** = "CF-1.8" ;
:**product_version** = 3. ;
:**format_version** = "CCI Data Standards v2.2" ;
:**summary** = "This dataset contains the surface elevation change of the Antarctic grounded ice sheet at 5.0km resolution on a polar stereo grid, at 5-year intervals, stepped by 1-year, derived from radar altimetry missions since 1991: ERS-1, ERS-2, ENVISAT, CryoSat-2, Sentinel-3A, and Sentinel-3A" ;
:**keywords** = "satellite,ice, ice sheets, ice growth/melt, cryospheric indicators, climate indicators" ;
:**id** = "ESACCI-AIS-L3C-SEC-MULTIMISSION-5KM-5YEAR-MEANS-1991-2021-fv1.nc" ;
:**naming_authority** = "cpom.org.uk" ;

:**keywords_vocabulary** = "NASA Global Change Master Directory (GCMD) Science Keywords" ;
:**date_created** = "20250525T224627Z" ;
:**project** = "Climate Change Initiative -European Space Agency" ;
:**region** = "Antarctic grounded ice" ;
:**grid_resolution** = "5.0km" ;
:**geospatial_lat_min** = -89.9674601532943 ;
:**geospatial_lat_max** = -56.7587107166777 ;
:**geospatial_lon_min** = 0.0592510435250638 ;
:**geospatial_lon_max** = 359.940748956475 ;
:**period_per_grid_slice** = "5 years" ;
:**number_of_sec_periods** = "30 years" ;
:**gia_correction_model** = "ij05" ;
:**data_start_time** = "1991-01-01T00:00:00Z" ;
:**data_end_time** = "2025-01-01T00:00:00Z" ;
:**time_coverage_start** = "19910101T000000Z" ;
:**time_coverage_end** = "20250101T000000Z" ;
:**key_variables** = "sec, sec_uncertainty" ;
:**spatial_resolution** = "5km grid" ;
:**dhdt_sw_version** = "0ded87aa6" ;
:**product_sw_version** = "0ded87aa6" ;
:**product_created** = "2021-05-25T22:46:27Z" ;
:**license** = "ESA CCI Data Policy: free and open access" ;
:**netCDF_version** = "NETCDF4" ;
}

The following is the netCDF CDL (ie the list of parameters and attributes) of a single-mission SEC product:

netcdf ESACCI-AIS-L3C-SEC-ENV-5KM-20020909-20120409-fv1 {

dimensions:
ny = 968 ;
nx = 1128 ;

variables:

float **sec**(ny, nx) ;
sec:long_name = "surface elevation change" ;
sec:units = "m/yr" ;
sec:source = "EV" ;
sec:grid_mapping = "grid_projection" ;

float **sec_uncertainty**(ny, nx) ;
sec_uncertainty:long_name = "uncertainty in surface elevation change" ;
sec_uncertainty:units = "m/yr" ;
sec_uncertainty:grid_mapping = "grid_projection" ;

float **x**(nx) ;
x:long_name = "Cartesian x-coordinate - easting, of centre of each grid cell" ;
x:units = "meters" ;
x:standard_name = "projection_x_coordinate" ;
x:min_val = -2817500. ;
x:binsize = 5000. ;

float **y**(ny) ;
y:long_name = "Cartesian y-coordinate - northing, of centre of each grid cell" ;
y:units = "meters" ;
y:standard_name = "projection_y_coordinate" ;
y:min_val = -2417500. ;
y:binsize = 5000. ;

char **grid_projection** ;
grid_projection:ellipsoid = "WGS84" ;

grid_projection:crs = "epsg:3031" ;
grid_projection:latitude_of_origin = -71. ;
grid_projection:grid_mapping_name = "polar_stereographic" ;
grid_projection:false_easting = 0. ;
grid_projection:false_northing = 0. ;
grid_projection:central_meridian = 0. ;

double **lat**(ny, nx) ;
lat:units = "degrees_north" ;
lat:standard_name = "latitude" ;
lat:long_name = "latitude coordinate" ;
lat:min_val = -89.9674601532943 ;
lat:max_val = -56.7587107166777 ;

double **lon**(ny, nx) ;
lon:units = "degrees_east" ;
lon:standard_name = "longitude" ;
lon:long_name = "longitude coordinate" ;
lon:min_val = 0.0592510435250638 ;
lon:max_val = 359.940748956475 ;

byte **surface_type**(ny, nx) ;
surface_type:_FillValue = -128b ;
surface_type:coordinates = "lon lat" ;
surface_type:long_name = "surface type from mask" ;
surface_type:flag_values = 0b, 1b, 2b, 3b, 4b ;
surface_type:flag_meanings = "ocean ice_free_land grounded_ice floating_ice lake_vostok" ;
surface_type:source = "https://nsidc.org/data/nsidc-0756/versions/2"
surface_type:valid_min = 0b ;
surface_type:valid_max = 4b ;
surface_type:comment = "Surface type identifier, for use in discriminating different surfaces types within the SEC grid; derived from the BedMachine Antarctica version 2 (Morlighem, 2020) datasets." ;

byte **basin_id**(ny, nx) ;
basin_id:_FillValue = -128b ;
basin_id:coordinates = "lon lat" ;
basin_id:long_name = "Glacialogical basin identification number" ;
basin_id:comment = "IMBIE glacialogical basin id number (Zwally et al., 2012) associated with each measurement. Values are : 0 (outside mask), 1-27 (basin values for Antarctica)" ;
basin_id:source = "IMBIE http://imbie.org/imbie-2016/drainage-basins/" ;

float **start_time** ;
start_time:comment = "the start time of the period used to calculate surface elevation change, in decimal years" ;
start_time:long_name = "start time" ;
start_time:units = "years" ;
start_time:time_string = "2002-09-09T00:00:00Z" ;

float **end_time** ;
end_time:comment = "the end time of the period used to calculate surface elevation change, in decimal years" ;
end_time:long_name = "end time" ;
end_time:units = "years" ;
end_time:time_string = "2012-04-09T23:59:59Z" ;

float **cell_time_lengths**(ny, nx) ;
cell_time_lengths:_FillValue = NaNf ;
cell_time_lengths:comment = "the length of time (in years) between first and last datapoints in each grid cell, used for surface elevation change calculation" ;
cell_time_lengths:long_name = "period covered by grid cell" ;
cell_time_lengths:units = "years" ;
cell_time_lengths:min_val = 4.98322104947975 ;
cell_time_lengths:max_val = 9.19988771614642 ;

float **cell_start_times**(ny, nx) ;
cell_start_times:_FillValue = NaNf ;
cell_start_times:comment = "the time of the first datapoint in each grid cell period, in years since 1991.0" ;
cell_start_times:long_name = "first time in grid cell" ;

cell_start_times:units = "years" ;
cell_start_times:min_val = 11.6904109589041 ;
cell_start_times:max_val = 15.9068493150685 ;

float **cell_end_times**(ny, nx) ;
cell_end_times:_FillValue = NaNf ;
cell_end_times:comment = "the time of the last datapoint in each grid cell period, in years since 1991.0" ;
cell_end_times:long_name = "last time in grid cell" ;
cell_end_times:units = "years" ;
cell_end_times:min_val = 17.0571936522195 ;
cell_end_times:max_val = 20.8902986750505 ;

// global attributes:
:**title** = "Antarctic Surface Elevation Change from the full mission period of EV at 5.0km resolution" ;
:**institution** = "University College London (UCL)" ;
:**reference** = "Trends in Antarctic Ice Sheet Elevation and Mass, Shepherd et al, GRL,2019,doi: 10.1029/2019GL082182" ;
:**history** = "2025-05-21T12:48:52Z - Product generated by CPOM Software Processor, commit 0ded87aa6" ;
:**tracking_id** = "83b1f760-ba2a-11eb-8c32-ecf4bbf106a0" ;
:**Conventions** = "CF-1.8" ;
:**product_version** = 3. ;
:**format_version** = "CCI Data Standards v2.2" ;
:**summary** = "This dataset contains the surface elevation change of the Antarctic grounded ice sheet at 5.0km resolution on a polar stereo grid, derived from the full mission period of EV" ;
:**keywords** = "satellite,ice, ice sheets, ice growth/melt, cryospheric indicators, climate indicators" ;
:**id** = "ESACCI-AIS-L3C-SEC-ENV-5KM-20020909-20120409-fv1.nc" ;
:**naming_authority** = "cpom.org.uk" ;
:**keywords_vocabulary** = "NASA Global Change Master Directory (GCMD) Science Keywords" ;
:**date_created** = "20250521T124852Z" ;
:**creator_name** = "University College London, CPOM" ;
:**creator_url** = "http://cpom.org.uk" ;
:**creator_email** = "cpom@leeds.ac.uk" ;
:**project** = "Climate Change Initiative -European Space Agency" ;
:**geospatial_lat_min** = -89.9674601532943 ;
:**geospatial_lat_max** = -56.7587107166777 ;
:**geospatial_lon_min** = 0.0592510435250638 ;
:**geospatial_lon_max** = 359.940748956475 ;
:**time_coverage_start** = "20020909T000000Z" ;
:**time_coverage_end** = "20120409T000000Z" ;
:**key_variables** = "sec,sec_uncertainty" ;
:**spatial_resolution** = "5km grid" ;
:**source** = "ENVISAT RA2 GDRv3" ;
:**source_mission** = "ENVISAT" ;
:**grid_resolution** = "5.0km" ;
:**epoch_length** = "140 days" ;
:**number_of_epochs** = "26" ;
:**gia_correction_model** = "ij05" ;
:**data_start_time** = "2002-09-09T00:00:00Z" ;
:**data_end_time** = "2012-04-09T23:59:59Z" ;
:**epoch_averaging_start_time** = "2002-07-02 00:00:00" ;
:**epoch_averaging_end_time** = "2012-06-19 00:00:00" ;
:**maximum_sec_filter** = "10.00 m/yr" ;
:**minimum_cell_time_coverage** = "50.00 % of period" ;
:**minimum_number_of_datapoints_per_cell** = "10" ;
:**sec_period_length** = "9.58 yrs" ;
:**power_correction_length_years** = "15.01 yrs" ;
:**power_correction_start_date** = "01 01 2005" ;
:**power_correction_end_date** = "01 01 2020" ;
:**surface_fit_sigma_filter** = 2. ;
:**surface_fit_max_model_fit_iterations** = "30" ;
:**surface_fit_max_linear_fit_iterations** = "3" ;
:**surface_fit_min_measurements_in_cell** = "20" ;
:**grid_sw_version** = "0bd217935" ;
:**surface_fit_sw_version** = "a280a90a0" ;
:**epoch_averaging_sw_version** = "a280a90a0" ;
:**dhdt_sw_version** = "0ded87aa6" ;

```
        :product_sw_version = "0ded87aa6" ;
        :product_created = "2025-05-21T12:48:52Z" ;
}
```

2.6 Available Software Tools

SEC products can be read by many netcdf readers or viewing tools. For the greatest flexibility in reading and further processing of the SEC products, users are recommended to use Python, the most widely used data science programming language.

2.7 References

McMillan. M, A.Shepherd. A.Sundal,K.Briggs, A.Muir,A.Ridout,A.Hogg,D.Wingham, Increased ice losses from Antarctica detected by CryoSat-2, doi.org/10.1002/2014GL060111

Ivins, E. R., and T. S. James (2005), Antarctic glacial isostatic adjustment: A new assessment, *Antarct. Sci.*, 17, 541–553.

Ravinder, N., Shepherd, A., Otosaka, I., Slater, T., Muir, A. and Gilbert, L., 2024. Greenland Ice Sheet elevation change from CryoSat-2 and ICESat-2. Geophysical Research Letters, 51(24), p.e2024GL110822.

Shepherd A, Gilbert L, Muir AS, Konrad H, McMillan M, Slater T, Briggs KH, Sundal AV, Hogg AE, Engdahl ME. 2019. Trends in Antarctic Ice Sheet Elevation and Mass. Geophysical Research Letters. 46(14), pp. 8174-8183

3 Ice Velocity (IV) Products

This chapter describes the Ice Velocity ECV parameter products.

In Phase 2 of the project, we continue the production Sentinel-1 derived IV retrieval over the Antarctic Ice Sheet margins to cover all the areas required for the product on MFID (Option 3). Development efforts are focused on integrating SAOCOM SAR data into the processing chain and testing InSAR-augmented ice velocity (IV) retrieval. Prototype products will be generated for selected areas of interest, generally adhering to the standard IV product specifications. However, variations in repeat-pass interval or resolution may occur and will be reflected in the filename. Additionally, new Ice Velocity Change (IVC) products will be developed and produced. These test products will be delivered as gridded maps, matching the grid size and spatial extent of the regional IV maps from which they are derived.

3.1 Product Geophysical Data Content

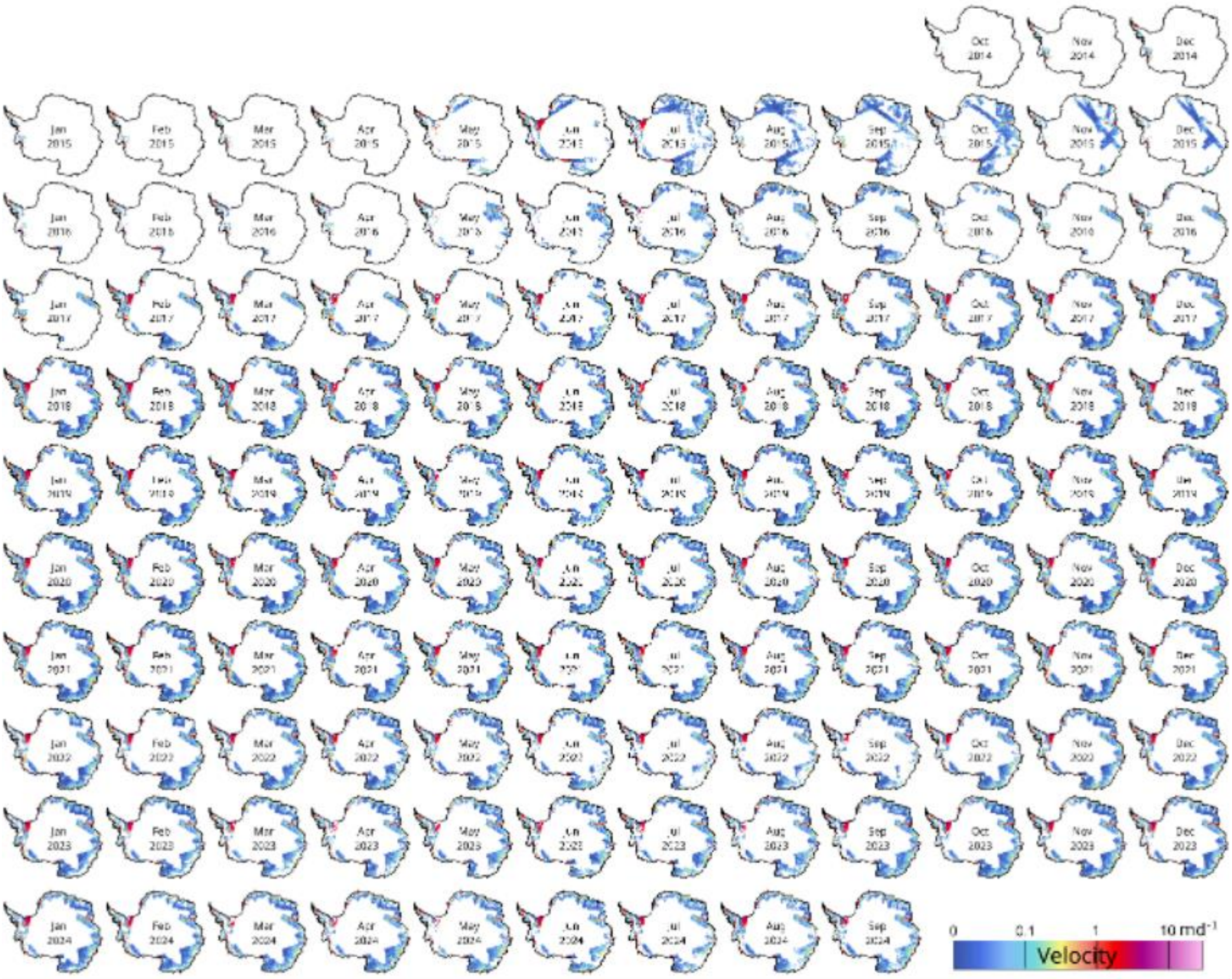
The main Ice Velocity (IV) products produced in Antarctic Ice Sheet CCI contain surface velocity maps of the Antarctic ice sheet that are derived from repeat-pass Copernicus Sentinel-1 (S1) synthetic aperture radar (SAR) data. The velocity maps are derived applying advanced iterative offset tracking techniques utilizing long stripes of S1 SAR data acquired in interferometric wide (IW) swath mode. The velocity maps cover all areas with S1 repeat-pass acquisitions in Antarctica, which are primarily restricted to the coastal margins.

Offset or feature tracking is a technique capable of acquiring ice flow velocity data over large areas at various temporal scales using either optical or SAR satellite imagery. The latter is suitable year-round and in all weather conditions. Offset tracking uses the displacement of surface features such as crevasses or rifts that move with the same speed as the ice, and are identifiable on two co-registered satellite images, to derive velocity based on image patch correlation. As opposed to InSAR, offset tracking works over short (days) as well as longer time spans (years), including in regions with fast flow as no coherence is required, and provides two components of the velocity vector.

The primary processor for IV generation is the ENVEO software package (ESP v2.1). ESP is a state-of-the-art IV retrieval algorithm designed for SAR sensors and has been tested rigorously through intercomparisons with other packages and extensive validation efforts. A key novel development for the IV retrieval algorithm in Antarctic Ice Sheet CCI+ is the implementation of an Ice Velocity Tidal Correction Module (IV-TCM), which is embedded in the IV module of ESP. The IV-TCM corrects the ice velocity on ice shelves and floating extensions of outlet glaciers (e.g. ice tongues) for tidally induced vertical motion using an external tide model (CATS2008; Erofeeva et al., 2019) and atmospheric pressure reanalysis data (ERA5; Hersberg et al., 2018).

A velocity grid derived from a repeat-pass satellite image/track pair represents the average ice surface velocity for the respective period. For Sentinel-1 acquisitions in Antarctica the repeat-pass period is 6 to 12 days. Track-by-track processing is applied for all continuous Sentinel-1 IW acquisitions in Antarctica. To improve coverage and reduce the noise, the individual 6 and 12-day repeat maps are merged to produce monthly and (multi-)annual mosaics over Antarctica (Figure 3-1). Individual results from different dates and different tracks are merged on a pointwise basis using a least square inversion that projects the displacement measured in radar geometry on the direction of the cartographic axes.

Figure 3-1:



Monthly IV mosaics of the Antarctic coastal margin for the period Oct 2014 till Sept 2024 derived from Copernicus Sentinel-1.

All IV products contain maps with the horizontal and vertical components of the velocity vector as well as the horizontal velocity magnitude in true meters per day. The horizontal surface velocities are derived from measured displacements in radar geometry (range, azimuth). The vertical velocity is derived from the interpolated height at the start and end position of the displacement vector taken from a DEM (Howat et al., 2019). Along with the ice velocity maps, the monthly and annual products include also valid pixel count maps providing the number of valid displacement estimates at the output pixel position used for creating the merged mosaic, as well as an uncertainty map that is based on the standard deviation (Table 3-1).

3.2 Product Data Format

Monthly and annual maps are provided in netCDF-4 format with separate layers for the velocity(-change) components: v_X, v_Y, v_Z and the magnitude of the horizontal components, and maps showing the valid pixel count (IV only) and uncertainty in both horizontal directions (stddev) (Table 3-1 and 3-2). The IV and IVC maps are provided at 200m x 200m grid spacing in Antarctic Polar Stereographic projection (EPSG:3031). Data type for the velocity is 32 bit floating-point. For all maps a NoData value of 3.4028234663852886e+38 is used.

Table 3-1: IV main data variables

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

Table 3-2: IVC main data variables

Variable name	Variable description	Type
land_ice_surface_easting_velocity_change	Ice velocity East component [m/day]	32-bit floating-point
land_ice_surface_northing_velocity_change	Ice velocity North component [m/day]	32-bit floating-point
land_ice_surface_vertical_velocity_change	Ice velocity Vertical component [m/day]	32-bit floating-point
land_ice_surface_velocity_magnitude_change	Ice velocity magnitude [m/day]	32-bit floating-point
land_ice_surface_easting_vel_change_stddev	Standard deviation [m/day] (Easting)	32-bit floating-point
land_ice_surface_northing_vel_change_stddev	Standard deviation [m/day] (Northing)	32-bit floating-point

The 6/12 day continuous repeat track ice velocity products are distributed through the ENVEO Cryoportal after registration (http://cryoportal.enveo.at/; see Chapter 6.1.2). These IV maps are provided in compressed zip format containing the IV fields in GeoTIFF format, gridded at 200m in Antarctic Polar Stereographic projection (EPSG:3031). The velocity grid for a given file represents the average velocity (in true meter per day) over the respective repeat pass period used for feature tracking as indicated in the file name (see below for file naming convention). Separate GeoTIFF files are provided for the velocity components and velocity magnitude. Along with the velocity grids a quicklook image and an xml file with a metadata file is provided (see chapter 3.5) Data type for the velocity is 32 bit floating-point. For all maps, a NoData value of 3.4028234663852886e+38 is used. Figure 3-2 shows an example of the gdalinfo output for an ice velocity map. Additionally, a metadata file (xml) and quicklook image (png) are provided.

```
Driver: GTiff/GeoTIFF
Files: antarctica_iv_200m_s1c_s1_t038_20250501_20250507_v1_2_vv.tif
Size is 3133, 4325
Coordinate System is:
PROJCRS["WGS 84 / Antarctic Polar Stereographic",
    BASEGEOGCRS["WGS 84",
        DATUM["World Geodetic System 1984",
            ELLIPSOID["WGS 84",6378137,298.257223563,
                LENGTHUNIT["metre",1]]],
        PRIMEM["Greenwich",0,
            ANGLEUNIT["degree",0.0174532925199433]],
        ID["EPSG",4326]],
    CONVERSION["Polar Stereographic (variant B)",
        METHOD["Polar Stereographic (variant B)",
            ID["EPSG",9829]],
        PARAMETER["Latitude of standard parallel",-71,
            ANGLEUNIT["degree",0.0174532925199433],
            ID["EPSG",8832]],
        PARAMETER["Longitude of origin",0,
            ANGLEUNIT["degree",0.0174532925199433],
            ID["EPSG",8833]],
        PARAMETER["False easting",0,
            LENGTHUNIT["metre",1],
            ID["EPSG",8806]],
        PARAMETER["False northing",0,
            LENGTHUNIT["metre",1],
            ID["EPSG",8807]]],
    CS[Cartesian,2],
        AXIS["(E)",north,
            MERIDIAN[90,
                ANGLEUNIT["degree",0.0174532925199433,
                    ID["EPSG",9122]]],
            ORDER[1],
            LENGTHUNIT["metre",1]],
        AXIS["(N)",north,
            MERIDIAN[0,
                ANGLEUNIT["degree",0.0174532925199433,
                    ID["EPSG",9122]]],
            ORDER[2],
            LENGTHUNIT["metre",1]]]
Data axis to CRS axis mapping: 1,2
Origin = (-2630800.000000000000000,1733200.000000000000000)
Pixel Size = (200.000000000000000,-200.000000000000000)
Metadata:
  AREA_OR_POINT=Area
Image Structure Metadata:
  COMPRESSION=LZW
  INTERLEAVE=BAND
Corner Coordinates:
Upper Left  (-2630800.000, 1733200.000) ( 56d37'21.61"W, 61d34'43.09"S)
Lower Left  (-2630800.000,  868200.000) ( 71d44'11.05"W, 64d53'44.98"S)
Upper Right (-2004200.000, 1733200.000) ( 49d 8'50.19"W, 65d57'29.11"S)
Lower Right (-2004200.000,  868200.000) ( 66d34'41.55"W, 70d 5'32.27"S)
Center      (-2317500.000, 1300700.000) ( 60d41'47.84"W, 65d53'18.92"S)
Band 1 Block=3133x1 Type=Float32, ColorInterp=Gray
  Description = vmcall
  NoData Value=3.4028235e+38
```

Figure 3-2 Example gdalinfo output for one of the IV maps distributed through the ENVEO Cryoportal.

3.3 File naming convention

The file naming convention of the monthly IV mosaics (provided as NetCDF) are according to the latest CCI Data Standards (see RD1).

Example IV: 20200801-ESACCI-L3C-AIS-IV-S1-1M_200m-fv1.0.nc

The file naming convention of the (annual) IVC mosaics (provided as NetCDF) follow the ones for IV:

Example for IVC product 2023-2024: 2023-2024-ESACCI-L3C-AIS-IVC-S1-1Y_200m-fv1.0.nc

For velocity files from repeat tracks distributed through the ENVEO Cryoportal (http://cryoportal.enveo.at/; see Chapter 6.1.2) the file naming convention is:

antarctica_iv_<gridspacing>_<sensor>_t<track#>_<date1>_date2>_<version>_<type>.<filetype>

- <gridspacing>: 200m
- <sensor>: s1 = Sentinel-1
- <type>: vx, vy, vz or vv (3 velocity components & horizontal magnitude respectively)
- <filetype> : tif (velocity maps), xml (metadata) or ql.png (quiclook)

Example: antarctica_iv_200m_s1_t169_20210125_20210131_v1_1_vx.tif

3.4 Product Grid and Projection

Ice Velocity maps and Ice Velocity Change maps are gridded at 200m x 200m. The map projection for all IV data products is Antarctic Polar Stereographic with a latitude of origin at -71°, central meridian at 0°, and using the WGS84 ellipsoid (EPSG:3031). Because of rapidly changing coastal configuration in Antarctica a land/ice/ocean mask is currently not applied for repeat track products, for monthly and annual maps masks are updated regularly.

3.5 Metadata Information

The metadata of the IV and IVC mosaics are embedded in the NetCDF file and are according to the latest CCI Data Standards [RD1]. For velocity files from repeat tracks distributed through the ENVEO Cryoportal (http://cryoportal.enveo.at/; see Chapter 6.1.2), a metadata file in xml format is included, containing information on the identification of the product (e.g. file name, content, size, creators, version, etc.), a brief description (methods, file naming, citation, etc.), information on the source data (satellites, sensor, track, date range, auxiliary data), geographic coverage and data file listing with brief description.

3.6 Product Known Limitations

The following lists some known product limitations. For further technical details we refer to the Algorithm Theoretical Baseline Document [RD2]:

1) The IV products contain 3 layers representing the horizontal (Easting, Northing) and the vertical components of velocity. It should be noted that this is 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 by the repeat image pair (e.g., 6 to 12 days for Sentinel-1). The monthly mosaics do not provide an exact average, but a least-square solution. Spatial gaps in some of the maps used for a monthly mosaic may be filled with data available from other maps, this can in some cases cause a jump in velocity.

3) For various reasons, the tracking software may fail 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 and 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. We apply a simple 3x3 median filter to get rid of outliers and a 5x5 distance-weighted first order plane fit to fill small gaps in the data, further filtering/gap filling is left to the user if required.

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.

5) In-situ GPS data for validation of ice velocity is only sparsely available. In absence of this, we therefore 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, we check the velocity results on stable terrain (rock outcrops), where no movement is expected.

InSAR performance for measuring ice motion is limited by a number of factors. The main limitations are:

- Ionosphere: at high latitude, the total electron content (TEC) of the ionosphere is very likely to vary (both in space and time) between two acquisitions. Different TEC introduce a phase delay related to the path travelled through the ionosphere, which can bias or mask the ice motion signal.
- Change in snow conditions: if snow surface undergoes change such as melting or snowfall, the change in the surface state can cause decorrelation. For this reason, InSAR shows better performance during the wintertime, during which snow conditions are more stable.
- Fast-moving areas: large displacements cause aliasing or decorrelation in interferograms. For this reason, fast-moving ice areas cannot be efficiently covered by Sentinel-1 C-Band data with 6-day revisit time. SAOCOM, operating at L-Band, on the other hand can also cover faster moving areas with an 8-day revisit time.

3.7 Available Software Tools

The ice velocity products are distributed as either NetCDF or GeoTIFF files. These product formats can be readily ingested and displayed by any GIS package (e.g., the popular open-source GIS package QGIS), and is largely self-documenting.

3.8 References

Erofeeva, S., Howard, S. L. and Padman, L. (2019) ‘CATS2008: Circum-Antarctic Tidal Simulation version 2008’. U.S. Antarctic Program (USAP) Data Center. doi: 10.15784/601235.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2018): ERA5 hourly data on pressure levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Howat, I. M., Porter, C., Smith, B. E., Noh, M.-J., and Morin, P.: The Reference Elevation Model of Antarctica, The Cryosphere, 13, 665-674, https://doi.org/10.5194/tc-13-665-2019, 2019.

4 Grounding Line Location (GLL) Products

This chapter describes the ECV parameter Grounding Line Location products. In the Phase 2 of the project we developed a method for an automatic delineation of the grounding line from the fringe pattern of the DInSAR interferograms. This new procedure can be applied to support or replace the manual delineation and should be noted in the GLL product. As a consequence 3 new attributes were added to the ESRI shape file and listed in Table 4.1:

- UUID - a string to uniquely identify the SAR scenes used for the creation of the interferograms and generation of the GLL segment
- DELINEATION - a string for mentioning the delineation type ("manual" or "automatic")
- DELINEATION_METHOD - a string with details on the parameters used in case of the automatic delineation

4.1 Product Geophysical Data Content

The grounding line is the transition between the grounded and the floating part of the ice shelf. Due to ocean tides and air pressure changes floating parts experience short term vertical changes unlike the grounded parts. The deformation due to the unequal vertical behaviour can be detected using SAR interferometry. The upper limit of flexure, a very good approximation of the actual grounding line, is mapped and provided in the GLL product.

4.2 Product Format

The product is delivered in the ESRI Shapefile data format. (https://en.wikipedia.org/wiki/Shapefile)

The ESRI Shapefile is a well-suited format for annotated geometric shapes if further geospatial analyses shall be performed.

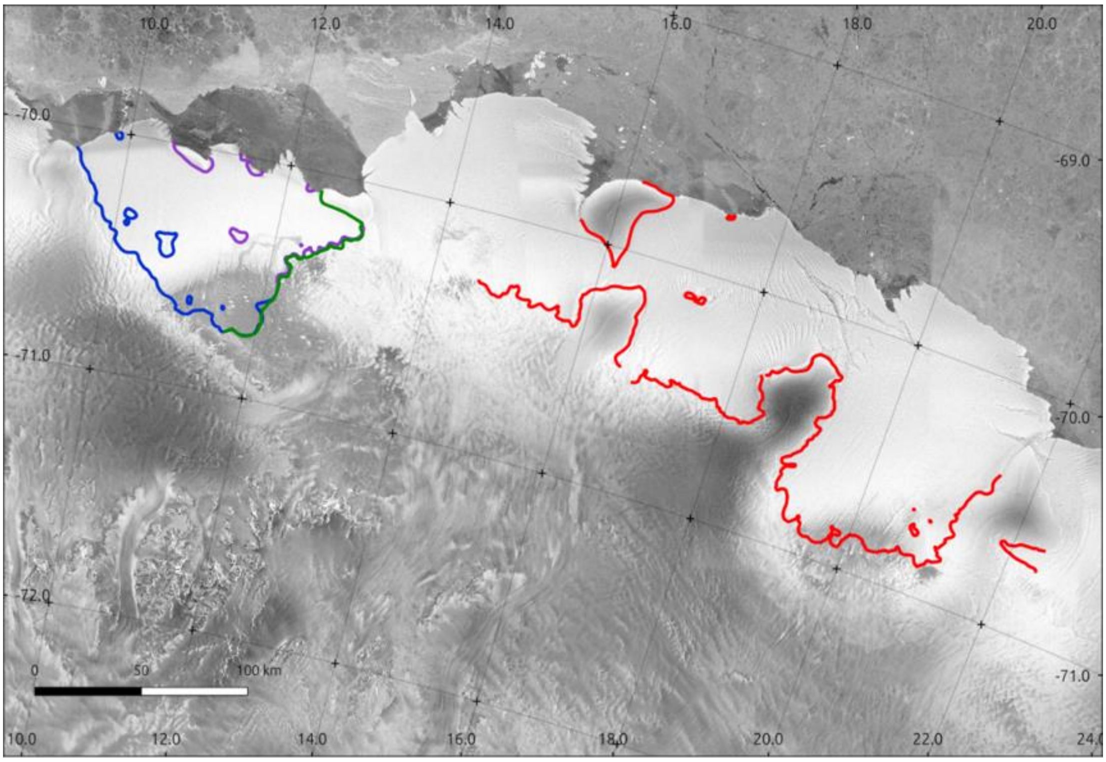


Figure 4-1: Sample GLL derived from ERS-1/2 (left in blue, purple, green) and Sentinel-1A (right in red). This subset will be used to explain the data formats. This product contains 4 GLLs.

4.3 Product Data Format

One possible application for the derived GLL product is the detection of GLL's retreat. A meaningful and interpretable comparison of GLLs however is not trivial and requires additional information such as time of image acquisition, ocean tide level, air pressure, etc.

The delivered GLL product internally contains many separate grounding line items. Each item has geometric information (location) along with attributes (metadata). It is obvious that, if already one parameter changes (e.g., the satellite track, the sensor or date/time), this grounding line segment cannot be connected to the others but must be a separate item with respect to time and the conditions (mainly ocean tides) under which it was acquired.

The product shown in Figure 4-1 contains four items (blue, purple, green and red lines). The attribute table of these four items (four lines) which provide the metadata (columns, not all are shown) is given in Figure 4-2.

	ıame	relorb	passdir	lookdir	m_pass	t1	t2	t3	t4	rp_lon	rp_lat	otl_t1	otl_t2	otl_t3
0	SEN	49	D	R	3	2015-05-25/02:09:21	2015-06-06/02:09:21	2015-06-18/02:09:22	NULL	17.86500000	-70.21700000	-0.27400000	-0.55200000	-0.26900000
1	ERS	163	D	R	2	1996-04-06/07:17:30	1996-04-05/07:17:30	NULL	NULL	11.76900000	-70.65200000	0.48300000	0.49100000	0.00000000
2	ERS	316	A	R	2	1996-05-21/23:58:10	1996-05-20/23:58:10	NULL	NULL	11.76900000	-70.65200000	-0.71500000	-0.88400000	0.00000000
3	ERS	130	A	R	2	1996-05-09/00:06:50	1996-05-08/00:06:50	NULL	NULL	11.76900000	-70.65200000	-0.51800000	-0.78300000	0.00000000

Show All Features

Figure 4-2: Screenshot of the attribute table (metadata) of the GLL items shown in Figure 4-1.

The attribute table is a distinct record which has the same attribute names for each line (shown in table 4.1). The geometry within one GLL item is represented by a *MultiLineString* which can contain numerous line segments no matter whether they are connected or not.

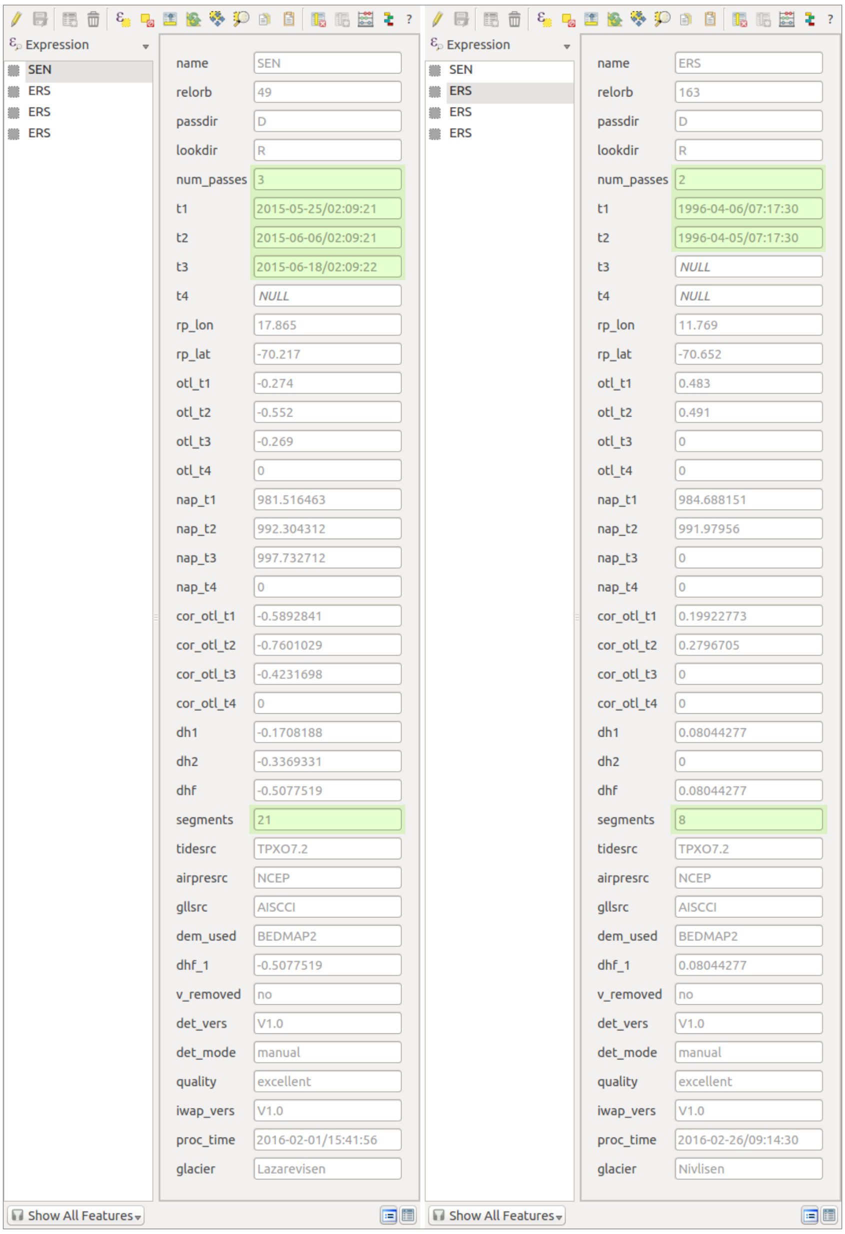
Table 4.1: Specification of the content stored in the attribute table. The data type notation is corresponding to the shapefile convention.

ID	Attribute Name	Type	Unit	Explanation
01	NAME	string	[-]	name of satellite: 'TSX': TerraSAR-X or TanDEM-X 'ERS': ERS1 or ERS2 'ENV': Envisat 'SEN': Sentinel-1A or Sentinel-1B 'RAD': Radarsat 'RA2': Radarsat-2 'ALO': ALOS Palsar 'AL2': ALOS Palsar 2 'COS': COSMO-Skymed
02	RELORB	int	[-]	relative orbit number
03	PASSDIR	string	[-]	satellite pass direction: ['ascending','descending']
04	LOOKDIR	string	[-]	satellite look direction: ['right','left']
05	NUM_PASSES	int	[-]	number of passes used [2, 3, 4]
06	T1	string	[UTC]	date/time of pass 1, string, 'YYYY-MM-DD HH:MM:SS'
07	T2	string	[UTC]	date/time of pass 2, string, 'YYYY-MM-DD HH:MM:SS'
08	T3	string	[UTC]	date/time of pass 3, string, 'YYYY-MM-DD HH:MM:SS' if not used ''
09	T4	string	[UTC]	date/time of pass 4, string, 'YYYY-MM-DD/HH:MM:SS' if not used ''
10	RP_LON	float	[deg]	longitude (WGS84) of reference point for tide/air pressure extraction given in decimal degrees, range: [-180.0 ... 180.0]
11	RP_LAT	float	[deg]	latitude (WGS84) of reference point for tide/air pressure extraction given in decimal degrees, range [-90.0 ... -59.0]
12	OTL_T1	float	[m]	predicted ocean tide level at (rp_lon, rp_lat) at t1
13	OTL_T2	float	[m]	predicted ocean tide level at (rp_lon, rp_lat) at t2
14	OTL_T3	float	[m]	predicted ocean tide level at (rp_lon, rp_lat) at t3 if not used: NULL
15	OTL_T4	float	[m]	predicted ocean tide level at (rp_lon, rp_lat) at t4 if not used: NULL
16	NAP_T1	float	[Pa]	interp. ncep air press. at (rp_lon, rp_lat) at t1
17	NAP_T2	float	[Pa]	interp. ncep air press. at (rp_lon, rp_lat) at t2
18	NAP_T3	float	[Pa]	interp. ncep air press. at (rp_lon, rp_lat) at t3 if not used: NULL
19	NAP_T4	float	[Pa]	interp. ncep air press. at (rp_lon, rp_lat) at t4 if not used: NULL
20	COR_OTL_T1	float	[m]	air press. corr. ocean tide level at (rp_lon, rp_lat) at t1
21	COR_OTL_T2	float	[m]	air press. corr. ocean tide level at (rp_lon, rp_lat) at t2
22	COR_OTL_T3	float	[m]	air press. corr. ocean tide level at (rp_lon, rp_lat) at t3

				if not used: NULL
23	COR_OTL_T4	float	[m]	air press. corr. ocean tide level at (rp_lon, rp_lat) at t4 if not used: NULL
24	DH1	float	[m]	expected vertical difference 1: dh1 = corr_otl_t2 - corr_otl_t1

25	DH2	float	[m]	expected vertical difference 2:
				if (num_passes == 4): dh2 = corr_otl_t4 - corr_otl_t3
				if (num_passes == 3): dh2 = corr_otl_t2 - corr_otl_t3
				if (num_passes == 2): dh2 = NULL

26	DHF	float	[m]	final height difference if num_passes == 4: dhf = dh2 - dh1 if num_passes == 3: dhf = dh2 + dh1 if num_passes == 2: dhf = dh1
27	TIDESRC	string	[-]	name of source for ocean tide model: ['CATS2008','TPXO7.2', ...]
28	AIRPRSRC	string	[-]	name of source for air pressure
29	DEM_USED	string	[-]	used DEM for geocoding: ['RAMP200', 'BEDMAP2', 'BAMBER', 'TDM Global DEM']
30	UUID	string	[-]	A unique identifier for each GLL segment in the format: <NAME>_<POLARIZATION>_<RELORB>_<T1>_<T2>_<T3>_<T4>_<PROCESSING_ID> e.g: SEN_HH_007_A_R_05_20170117050825_20170123050906_20170129050824________________000010
31	DELINEATION	string	[-]	delineation type: ['manual','automatic']
32	DELINEATION_METHOD	string	[-]	Identifier for the used method for automatic delineation "ml_256_100" for the ML network proposed here https://doi.org/10.5194/tc-19-2431-2025 "" for manual delineations



	SEN	ERS
name	SEN	ERS
relorb	49	163
passdir	D	D
lookdir	R	R
num_passes	3	2
t1	2015-05-25/02:09:21	1996-04-06/07:17:30
t2	2015-06-06/02:09:21	1996-04-05/07:17:30
t3	2015-06-18/02:09:22	NULL
t4	NULL	NULL
rp_lon	17.865	11.769
rp_lat	-70.217	-70.652
otl_t1	-0.274	0.483
otl_t2	-0.552	0.491
otl_t3	-0.269	0
otl_t4	0	0
nap_t1	981.516463	984.688151
nap_t2	992.304312	991.97956
nap_t3	997.732712	0
nap_t4	0	0
cor_otl_t1	-0.5892841	0.19922773
cor_otl_t2	-0.7601029	0.2796705
cor_otl_t3	-0.4231698	0
cor_otl_t4	0	0
dh1	-0.1708188	0.08044277
dh2	-0.3369331	0
dhf	-0.5077519	0.08044277
segments	21	8
tidesrc	TPXO7.2	TPXO7.2
airpresrc	NCEP	NCEP
gllsrc	AISCCI	AISCCI
dem_used	BEDMAP2	BEDMAP2
dhf_1	-0.5077519	0.08044277
v_removed	no	no
det_vers	V1.0	V1.0
det_mode	manual	manual
quality	excellent	excellent
iwap_vers	V1.0	V1.0
proc_time	2016-02-01/15:41:56	2016-02-26/09:14:30
glacier	Lazarevisen	Nivlisen

Figure 4-3: Sample attribute table for two items. On the left side a Sentinel-1 derived (double difference) GLL. The GLL shown on the right side is based on a single interferogram from ERS.

Figure 4-3 shows sample attribute tables for two items. The table on the left side represents a dataset derived from Sentinel-1A. The one on the right side is based on ERS data. The Sentinel-1A GLL was derived from double differences of three subsequent image acquisitions as it can be seen from t1 to t3. The ERS derived GLL originates only from a single difference (t1 and t2) which is possible due to the short time interval of 24 hours between the acquisitions in which the effect of velocity is small, in particular in that region. Ocean tide level, air pressure and corrected height differences between acquisitions are also provided.

4.4 Product Grid and Projection

All products are delivered in the same reference system and projection namely WGS 84 Antarctic Polar Stereographic, EPSG:3031 (https://spatialreference.org/ref/epsg/3031/)

If a user requires another projection the shapefile can simply be opened with QGIS. A right click on the loaded layer allows saving it again – the new projection can be set in the save dialog and all coordinates will be converted.

4.5 Product Known Limitations

SAR interferometry has been applied to detect and map grounding lines. The generation of grounding lines requires suitable repeat pass SAR image pairs with sufficient coherence to form two independent interferograms acquired at different tidal conditions. The repeat interval of the acquisitions must not be too long, otherwise temporal decorrelation will prohibit the characteristic fringe pattern required for mapping.

4.6 Available Software Tools

The GLL product is distributed as ESRI shapefile which is supported from almost all GIS packages. Besides commercial packages like ArcInfo, QGIS is a freely available and powerful open-source packages (http://www.qgis.org).

5 Gravimetric Mass Balance (GMB) Products

This chapter describes the Gravimetric Mass Balance (GMB) ECV parameter products.

In Phase 2 of the project we have continued updating the time series for the extended time period of the GRACE-FO mission as well as for updates of the underlying monthly gravity field solutions from RL06 to RL06.3. We have implemented an ellipsoidal correction, by which the mass loss estimate for the entire AIS became about 10% larger. We have implemented an algorithm to fill the 11-month gap between the GRACE and the GRACE-FO time series, by utilizing surface mass balance modeling output.

5.1 Product Geophysical Data Content

The GMB product comprises two different datasets: (1) the GMB gridded product and (2) the GMB basin product. The GMB gridded product contains time series of the change in mass of the AIS on a regular 50km x 50km grid covering the entire AIS. Time series of basin averaged changes in ice mass are provided in the GMB basin product. Basin averaged time series are derived for 26 drainage basins and the total areas of the Antarctic Peninsula, the East Antarctic Ice Sheet, the West Antarctic Ice Sheet and the entire Antarctic Ice Sheet. Mass balance estimates for every basin complete the GMB basin product. Each mass balance estimate is the linear component of a linear, periodic (periods: 1 year, 1/2 year) and quadratic model fitted to the entire time series of basin averaged changes in ice mass. Both GMB products have a temporal resolution of one month and cover the period from 04/2002 until present. Quarterly updates extend the time series as soon as new GRACE-FO monthly solutions are available.

Both GMB products are derived from GRACE/GRACE-FO monthly gravity field solutions with a maximum spherical harmonic degree l_{max}=90 using the regional integration approach based on tailored sensitivity kernels (Groh & Horwath, 2021). This algorithm was selected during the open Round Robin experiment conducted during the first phase of the AIS CCI project (Groh et al., 2019). Temporal changes in solid Earth mass caused by glacial isostatic adjustment (GIA) are corrected for by using the GIA model IJ05_R2 (Ivins et al, 2013). The GRACE/GRACE-FO solution series CSR RL06.3 (Bettadpur 2018, Save 2019) provided by the Center for Space Research (University of Texas at Austin) (http://www2.csr.utexas.edu/grace/RL06.html) is utilized for the GMB product generation. The temporal evolution in ice mass provided by the GMB products represents changes in mass relative to a reference value. This reference value is defined to be the GRACE-derived mass as of 2011-01-01. Technically, this value is derived from a linear, periodic (periods: 1 year, 1/2 year) and quadratic model fitted to the monthly solutions in the period 2002-08 – 2016-08.

5.2 Product Data Format

The GMB gridded product is available in the following three file formats:

1. NetCDF (*AIS_GMB_grid.nc*)
2. GeoTIFF (*AIS_GMB_grid.tif*)
3. ASCII (*AIS_GMB_grid.dat*)

The netCDF-4 classic file follows the CF conventions in version 1.7. The metadata embedded in the netcdf file are according to the latest CCI Data Standards [RD1]. Changes in ice mass are stored in the netCDF variable *dm* [kg/m^2]. Beside the projected x- and y-coordinates of the grid cell centres, corresponding ellipsoidal latitudes (*lat*) and longitudes (*lon*) are also given. In addition, each grid cell's area (*area*) on the ellipsoid is provided. Times are indicated in two different formats: modified Julian date (*time*) and decimal years (*time_dec*). Additional information on the product and the generating institution are stored in the global attributes. An overview of all variables, dimensions, units and global attributes is given by the following netCDF header information (ncdump –h) of the initial product release:

```
netcdf AIS_GMB_grid {
dimensions:
x = 117 ;
y = 97 ;
time = 187 ;
variables:
double x(x) ;
x:long_name = "x-coordinate" ;
x:standard_name = "projection_x_coordinate" ;
x:units = "m" ;
x:actual_range = -2900000., 2900000. ;
x:axis = "X" ;
double y(y) ;
y:long_name = "y-coordinate" ;
y:standard_name = "projection_y_coordinate" ;
y:units = "m" ;
y:actual_range = -2400000., 2400000. ;
y:axis = "Y" ;
double time(time) ;
time:long_name = "modified julian date" ;
time:standard_name = "time" ;
time:units = "days since 1858-11-17 00:00:00" ; time:actual_range = 52382., 59046.5 ;
time:axis = "T" ;
double time_dec(time) ;
time_dec:long_name = "decimal year" ;
time_dec:units = "year" ;
time_dec:actual_range = 2002.29295003422, 2020.54072553046 ; double lon(y, x) ;
lon:long_name = "longitude" ;
lon:units = "degrees_east" ;
lon:actual_range = -178.806511, 180. ;
double lat(y, x) ;
lat:long_name = "latitude" ;
lat:units = "degrees_north" ;
lat:actual_range = -90., -56.319983 ;
double dm(time, y, x) ;
dm:_FillValue = NaN ;
dm:long_name = "change in ice mass" ;
dm:standard_name = "change_in_land_ice_amount" ;
dm:units = "kg/m^2" ;
dm:actual_range = -5756.2, 4643.8 ;
double area(y, x) ;
area:long_name = "grid cell area on the ellipsoid" ; area:standard_name = "cell_area" ;
area:units = "m^2" ;
area:actual_range = 2217500967., 2641925416. ;
char crs ;
crs:grid_mapping_name = "polar_stereographic" ; crs:latitude_of_projection_origin = "-90" ;
crs:longitude_of_prime_meridian = "0" ;
crs:straight_vertical_longitude_from_pole = "0" ;
crs:standard_parallel = "-71." ;
crs:semi_major_axis = "6378137." ;
crs:inverse_flattening = "298.257223563" ;
crs:false_northing = "0" ;
crs:false_easting = "0" ;
crs:spatial_ref = "PROJCS[\"WGS 84 / Antarctic Polar Stereographic\",GEOGCS[\"WGS
84\",DATUM[\"WGS_1984\",SPHEROID[\"WGS
84\",6378137,298.257223563,AUTHORITY[\"EPSG\",\"7030\"]],AUTHORITY[\"EPSG\",\"6326\"]],PRIMEM[\"G
reenwich\",0,AUTHORITY[\"EPSG\",\"8901\"]],UNIT[\"degree\",0.01745329251994328,AUTHORITY[\"EPSG\"
,\"9122\"]],AUTHORITY[\"EPSG\",\"4326\"]],UNIT[\"metre\",1,AUTHORITY[\"EPSG\",\"9001\"]],PROJECTI
ON[\"Polar_Stereographic\"],PARAMETER[\"latitude_of_origin\",-
71],PARAMETER[\"central_meridian\",0],PARAMETER[\"scale_factor\",1],PARAMETER[\"false_easting\",0
],PARAMETER[\"false_northing\",0],AUTHORITY[\"EPSG\",\"3031\"],AXIS[\"Easting\",UNKNOWN],AXIS[\"N
orthing\",UNKNOWN]]" ;
crs:long_name = "coordinate reference system" ;
// global attributes:
:title = "ESA CCI AIS Gravimetric Mass Balance Gridded Product" ;
:institution = "TU Dresden, Chair of Geodetic Earth System Research" ;
:source = "GRACE/GRACE-FO L2 monthly solutions provided by Center for Space Research
(CSR RL06)" ;
:history = "2021-02-26: version 3.0 tracking_id d1fc87d6-6b3c-4b1b-8150-
11afa029ac1a, " ;
:references = "AIS_cci Product User Guide (https://climate.esa.int/en/projects/icesheets-antarctic/key-documents/)" ;
:tracking_id = "d1fc87d6-6b3c-4b1b-8150-11afa029ac1a" ;
:Conventions = "CF-1.7" ;
:netCDF_version = "netCDF-4_classic" ;
:product_version = "3.0" ;
:format_version = "CCI Data Standards v2.2" ;
:summary = "GRACE/GRACE-FO-derived time series of gridded Antarctic ice mass changes
with respect to the mass as of 2011-01-01 according to a linear, periodic (periods: 1 year, 1/2
year) and quadratic model fitted to the monthly solutions in the period 2002-08 - 2016-08" ;
:gia_model = "GIA correction: IJ05_R2 (https://doi.org/10.1002/jgrb.50208)" ;
:keywords = "ESA CCI, Antarctica, Ice Sheet Mass Balance, GRACE, GRACE-FO" ;
:id = "20210226-ESACCI-AIS-L3C-GMB-GRID-fv3.0.nc" ;
:naming_authority = "tu-dresden.de/bu/umwelt/geo/ipg/gef" ;
:keyword_vocabulary = "GCMD" ;
:cdm_data_type = "Grid" ;
:date_created = "2021-02-26" ;
:creator_name = "Andreas Groh, Martin Horwath" ;
:creator_url = "https://tu-dresden.de/bu/umwelt/geo/ipg/gef" ;
```

```
:creator_email = "martin.horwath@tu-dresden.de" ;
:project = "Climate Change Initiative - European Space Agency" ;
:geospatial_lat_min = "-90" ;
:geospatial_lat_max = "-60" ;
:geospatial_lon_min = "-180" ;
:geospatial_lon_max = "180" ;
:geospatial_vertical_min = "0" ;
:geospatial_vertical_max = "0" ;
:time_coverage_start = "2002-04-18" ;
:time_coverage_end = "2020-07-16" ;
:time_coverage_duration = "P18Y04M" ;
:time_coverage_resolution = "P1M" ;
:standard_name_vocabulary = "CF Standard Name Table v77" ;
:license = "ESA CCI Data Policy: free and open access" ;
:platform = "GRACE, GRACE-FO" ;
```

Using the freely available tool gdal_translate from the Geophysical Data Abstraction Library (www.gdal.org), the netCDF file is converted into a georeferenced TIFF file (GeoTIFF). The netCDF variable *time* (modified Julian date) is used as time dimension in the multi-band GeoTIFF file, whereas the number of bands is identical to the number of time slices. All netCDF metadata are preserved. The following dump (gdal_info) from the GeoTIFF file of the initial product release gives an overview of the included variables and metadata (output truncated after band 2):

```
Driver: GTiff/GeoTIFF
Files: product/AIS_GMB_grid.tif
       product/AIS_GMB_grid.tif.aux.xml
Size is 117, 97
Coordinate System is:
PROJCRS["WGS 84 / Antarctic Polar Stereographic",
    BASEGEOGCRS["WGS 84",
        DATUM["World Geodetic System 1984",
            ELLIPSOID["WGS 84",6378137,298.257223563,
                     LENGTHUNIT["metre",1]]],
        PRIMEM["Greenwich",0,
            ANGLEUNIT["degree",0.0174532925199433]],
        ID["EPSG",4326]],
    CONVERSION["Antarctic Polar Stereographic",
        METHOD["Polar Stereographic (variant B)",
            ID["EPSG",9829]],
        PARAMETER["Latitude of standard parallel",-71,
            ANGLEUNIT["degree",0.0174532925199433],
            ID["EPSG",8832]],
        PARAMETER["Longitude of origin",0,
            ANGLEUNIT["degree",0.0174532925199433],
                ID["EPSG",8833]],
        PARAMETER["False easting",0,
            LENGTHUNIT["metre",1],
            ID["EPSG",8806]],
        PARAMETER["False northing",0,
            LENGTHUNIT["metre",1],
            ID["EPSG",8807]]],
    CS[Cartesian,2],
      AXIS["(E)",north,
            MERIDIAN[90,
                ANGLEUNIT["degree",0.0174532925199433]],
            ORDER[1],
            LENGTHUNIT["metre",1]],
        AXIS["(N)",north,
            MERIDIAN[0,
                ANGLEUNIT["degree",0.0174532925199433]],
            ORDER[2],
            LENGTHUNIT["metre",1]],
      USAGE[
        SCOPE["unknown"],
        AREA["Antarctica"],
        BBOX[-90,-180,-60,180]],
    ID["EPSG",3031]]
Data axis to CRS axis mapping: 1,2
Origin = (-2925000.000000000000000,2425000.000000000000000)
Pixel Size = (50000.000000000000000,-50000.000000000000000)
Metadata:
  AREA_OR_POINT=Area
  COLORINTERP=Gray
  dm#actual_range={-5756.2,4643.8}
  dm#long_name=change in ice mass
  dm#standard_name=change_in_land_ice_amount
  dm#units=kg/m^2
  dm#_FillValue=-nan
  NC_GLOBAL#cdm_data_type=Grid
  NC_GLOBAL#Conventions=CF-1.7
  NC_GLOBAL#creator_email=martin.horwath@tu-dresden.de
  NC_GLOBAL#creator_name=Andreas Groh, Martin Horwath
  NC_GLOBAL#creator_url=https://tu-dresden.de/bu/umwelt/geo/ipg/gef
  NC_GLOBAL#date_created=2021-02-26
  NC_GLOBAL#format_version=CCI Data Standards v2.2
  NC_GLOBAL#geospatial_lat_max=-60
  NC_GLOBAL#geospatial_lat_min=-90
  NC_GLOBAL#geospatial_lon_max=180
```

```
  NC_GLOBAL#geospatial_lon_min=-180
  NC_GLOBAL#geospatial_vertical_max=0
  NC_GLOBAL#geospatial_vertical_min=0
  NC_GLOBAL#gia_model=GIA correction: IJ05_R2 (https://doi.org/10.1002/jgrb.50208)
  NC_GLOBAL#history=2021-02-26: version 3.0 tracking_id d1fc87d6-6b3c-4b1b-8150-11afa029ac1a,
  NC_GLOBAL#id=20210226-ESACCI-AIS-L3C-GMB-GRID-fv3.0.nc
  NC_GLOBAL#institution=TU Dresden, Chair of Geodetic Earth System Research
  NC_GLOBAL#keywords=ESA CCI, Antarctica, Ice Sheet Mass Balance, GRACE, GRACE-FO
  NC_GLOBAL#keyword_vocabulary=GCMD
  NC_GLOBAL#key_variables=change_in_land_ice_amount
  NC_GLOBAL#license=ESA CCI Data Policy: free and open access
  NC_GLOBAL#naming_authority=tu-dresden.de/bu/umwelt/geo/ipg/gef
  NC_GLOBAL#netCDF_version=netCDF-4_classic
  NC_GLOBAL#platform=GRACE, GRACE-FO
  NC_GLOBAL#product_version=3.0
  NC_GLOBAL#project=Climate Change Initiative - European Space Agency
  NC_GLOBAL#references=AIS_cci Product User Guide (https://climate.esa.int/en/projects/ice-sheets-antarctic/key-documents/)
  NC_GLOBAL#sensor=KBR, ACC, GPS
  NC_GLOBAL#source=GRACE/GRACE-FO L2 monthly solutions provided by Center for Space Research (CSR RL06)
  NC_GLOBAL#spatial_resolution=data resolution: ~350km, grid resolution: 50x50km^2
  NC_GLOBAL#standard_name_vocabulary=CF Standard Name Table v77
  NC_GLOBAL#summary=GRACE/GRACE-FO-derived time series of gridded Antarctic ice mass changes with respect to the mass as of 2011-01-01 according
to a linear, periodic (periods: 1 year, 1/2 year) and quadratic model fitted to the monthly solutions in the period 2002-08 - 2016-08
  NC_GLOBAL#time_coverage_duration=P18Y04M
  NC_GLOBAL#time_coverage_end=2020-07-16
  NC_GLOBAL#time_coverage_resolution=P1M
  NC_GLOBAL#time_coverage_start=2002-04-18
  NC_GLOBAL#title=ESA CCI AIS Gravimetric Mass Balance Gridded Product
  NC_GLOBAL#tracking_id=d1fc87d6-6b3c-4b1b-8150-11afa029ac1a
  NETCDF_DIM_EXTRA={time}
  NETCDF_DIM_time_DEF={187,6}

NETCDF_DIM_time_VALUES={52382,52404.5,52502.5,52533,52563.5,52594,52624.5,52655.5,52685,52714.5,52745,52770.5,52836.5,52867.5,52898,52928.5,5
2959,52989.5,53011.5,53052,53080.5,53111,53141.5,53172,53202.5,53233.5,53264,53294.5,53325,53355.5,53386.5,53416,53445.5,53476,53506.5,53537,
53567.5,53598.5,53629,53659.5,53690,53720.5,53751.5,53781,53810.5,53841,53871.5,53902,53932.5,53963.5,53994,54024.5,54055,54085.5,54116.5,541
45.5,54175.5,54206,54236.5,54267,54297.5,54328.5,54359,54389.5,54420,54450.5,54481.5,54511.5,54541.5,54572,54602.5,54633,54663.5,54694.5,5472
5,54755.5,54786,54816.5,54847.5,54877,54906.5,54937,54967.5,54998,55028.5,55059.5,55090,55120.5,55151,55181.5,55212.5,55242,55271.5,55302,553
32.5,55363,55393.5,55424.5,55455,55485.5,55516,55544.5,55610.5,55636.5,55667,55697.5,55760.5,55789.5,55820,55850.5,55865.5,55923,55942.5,5597
2.5,56002.5,56021,56094,56124.5,56155.5,56183.5,56249.5,56277.5,56308.5,56337,56403,56428.5,56459,56489.5,56581.5,56612,56642.5,56666,56733.5
,56763,56793.5,56821,56885.5,56916,56946.5,56977,57044.5,57068,57097.5,57128,57139,57218.5,57250.5,57279.5,57379,57403.5,57432,57463.5,57528,
57555,57584.5,57621.5,57719.5,57746.5,57774,57843.5,57867.5,57886,57914.5,58285,58309,58422.5,58438,58468.5,58499.5,58529,58558.5,58589,58619
.5,58650,58680.5,58711.5,58742,58772.5,58803,58833.5,58864.5,58894.5,58924.5,58955,58985.5,59016,59046.5}
  time#actual_range={52382,59046.5}
  time#axis=T
  time#long_name=modified julian date
  time#standard_name=time
  time#units=days since 1858-11-17 00:00:00
  x#actual_range={-2900000,2900000}
  x#axis=X
  x#long_name=x-coordinate
  x#standard_name=projection_x_coordinate
  x#units=m
  y#actual_range={-2400000,2400000}
  y#axis=Y
  y#long_name=y-coordinate
  y#standard_name=projection_y_coordinate
  y#units=m
Image Structure Metadata:
  INTERLEAVE=PIXEL
Corner Coordinates:
Upper Left  (-2925000.000, 2425000.000) ( 50d20'21.25"W, 56d 1'20.91"S)
Lower Left  (-2925000.000,-2425000.000) (129d39'38.75"W, 56d 1'20.91"S)
Upper Right ( 2925000.000, 2425000.000) ( 50d20'21.25"E, 56d 1'20.91"S)
Lower Right ( 2925000.000,-2425000.000) (129d39'38.75"E, 56d 1'20.91"S)
Center      (    0.0000000,    0.0000000) (  0d 0' 0.01"E, 90d 0' 0.00"S)
Band 1 Block=117x1 Type=Float32, ColorInterp=Gray
  NoData Value=nan
  Metadata:
    actual_range={-5756.2,4643.8}
    long_name=change in ice mass
    NETCDF_DIM_time=52382
    NETCDF_VARNAME=dm
    standard_name=change_in_land_ice_amount
    units=kg/m^2
    _FillValue=-nan
Band 2 Block=117x1 Type=Float32, ColorInterp=Undefined
  NoData Value=nan
  Metadata:
    actual_range={-5756.2,4643.8}
    long_name=change in ice mass
    NETCDF_DIM_time=52404.5
    NETCDF_VARNAME=dm
    standard_name=change_in_land_ice_amount
    units=kg/m^2
    _FillValue=-nan
```

Finally, the GMB gridded product is also provided in a simple ASCII file format. For each grid point the mass change time series is given in one line using the following format:

x y lat lon area dm1 dm2 dm3 …

Grid points outside the ice sheet are set to "NaN". The file header (lines starting with "#") contains all metadata, the time steps both as modified Julian date and as decimal year as well as a description of the file format and the units. The ASCII file may look like the following sample (truncated after grid point 3 and time step 3):

```
# title: ESA CCI AIS Gravimetric Mass Balance Gridded Product
# institution: TU Dresden, Chair of Geodetic Earth System Research
# project: Climate Change Initiative - European Space Agency
# source: GRACE/GRACE-FO L2 monthly solutions provided by Center for Space Research (CSR RL06)
# summary: GRACE/GRACE-FO-derived time series of gridded Antarctic ice mass changes with respect to the mass as of 2011-01-01 according to a
linear, periodic (periods: 1 year, 1/2 year) and quadratic model fitted to the monthly solutions in the period 2002-08 - 2016-08
# gia_model: GIA correction: IJ05_R2 (https://doi.org/10.1002/jgrb.50208)
# reference: AIS_cci Product User Guide (https://climate.esa.int/en/projects/ice-sheets-antarctic/key-documents/)
# time_coverage_start: 2002-04-18
# time_coverage_end: 2020-07-16
# product_version: 3.0
# date_created: 2021-02-26
# contact: martin.horwath@tu-dresden.de
# creator_name: Andreas Groh, Martin Horwath
# creator_ur l: https://tu-dresden.de/bu/umwelt/geo/ipg/gef
# creator_email: martin.horwath@tu-dresden.de
#
# time_dec decimal_year: 2002.293 2002.355 2002.623 …
# time_modified_julian_days: 52382.0 52404.5 52502.5 …
# x [m], y[m], lat [°], lon [°], area [m^2], dm1 [kg/m^2], dm2 [kg/m^2], ...
-2900000 -2400000 -56.319983 -129.610688 2217500967     NaN       NaN     NaN ….
-2900000 -2350000 -56.588120 -129.019400 2223752627     NaN       NaN     NaN ….
-2900000 -2300000 -56.853194 -128.418055 2229898122     NaN       NaN     NaN ….
```

The time series of the GMB basin product is available in ASCII format (*AIS_GMB_basin.dat*). For each time step the basin-averaged mass change (dm) and the corresponding accuracy measure (sigma dm) for all basins is given in one line using the following format:

'time_dec (decy)' 'time (mjd)' 'dm basin1' 'sigma_dm region1' …

The file header (lines starting with "#") contains all metadata, the list of regions as well as a description of the file format and the units. The ASCII file may look like the following sample (truncated after time step 3):

```
# title: ESA CCI AIS Gravimetric Mass Balance Basin Product
# institution: TU Dresden, Chair of Geodetic Earth System Research
# project: Climate Change Initiative - European Space Agency
# source: GRACE/GRACE-FO L2 monthly solutions provided by Center for Space Research (CSR RL06)
# summary: GRACE/GRACE-FO-derived time series of basin-averaged Antarctic ice mass changes with respect to the mass as of 2011-01-01 according
to a linear, periodic (periods: 1 year, 1/2 year) and quadratic model fitted to the monthly solutions in the period 2002-08 - 2016-08.
# error_estimates: Provided error estimates of the monthly mass change estimates solely account for the white noise component. Systematic
errors (e.g. errors in the GIA correction) are included in the error estimates of the derived linear trends.
# gia_model: GIA correction: IJ05_R2 (https://doi.org/10.1002/jgrb.50208)
#     regions:     Regions     1-24,27:     drainage     basins     according     to     Zwally     et     al.     (2012,
http://icesat4.gsfc.nasa.gov/cryo_data/ant_grn_drainage_systems.php), 28: Northern Peninsula, 29: Antarctic Peninsula, 30: East Antarctica,
31: West Antarctica, 32: Antarctic Ice Sheet
# reference: AIS_cci Product User Guide (https://climate.esa.int/en/projects/ice-sheets-antarctic/key-documents/)
# time_coverage_start: 2002-04-18
# time_coverage_end: 2020-07-16
# product_version: 3.0
# date_created: 2021-02-26
# creator_name: Andreas Groh, Martin Horwath
# creator_url: https://tu-dresden.de/bu/umwelt/geo/ipg/gef
# creator_email: martin.horwath@tu-dresden.de
#
# regions: AIS01 AIS02 AIS03 AIS04 AIS05 AIS06 AIS07 AIS08 AIS09 AIS10 AIS11 AIS12 AIS13 AIS14 AIS15 AIS16 AIS17 AIS18 AIS19 AIS20 AIS21 AIS22
AIS23 AIS24 AIS27 AIS28 AIS29 AIS30 AIS31 AIS32
# time_dec [decimal year], time [modified julian date], dm region1 [kg], sigma_dm region1 [kg], ...
2002.293 52382.0 -9.1008e+13  1.4629e+13 -3.8313e+13  9.5569e+12 -1.1507e+14  1.4067e+13 -7.2561e+13  8.1268e+12 -4.6926e+13  9.8725e+12 -
8.2663e+13  1.1800e+13 -1.1373e+14  1.7516e+13 -6.1997e+13  1.0035e+13 -1.1021e+12  5.9916e+12 -1.5613e+13  9.1360e+12 -1.4763e+12  6.3605e+12
-7.6022e+13  1.4084e+13  3.4109e+13  1.6391e+13  8.7739e+13  1.3989e+13  3.3804e+13  9.3549e+12 -9.4372e+12  5.5530e+12 -6.3570e+13  1.7664e+13
-1.4115e+14  6.6116e+12 -4.4158e+13  5.5367e+12  2.0790e+14  7.3725e+12  4.0063e+14  9.5656e+12  3.1205e+14  8.6005e+12  4.1164e+13  5.5585e+12
3.6535e+13  8.4020e+12 -1.9024e+13  8.1936e+12  1.8554e+14  1.2020e+13  2.0306e+14  1.8390e+13 -5.4284e+14  6.6378e+13  6.8543e+14  2.7032e+13
3.4565e+14  8.4383e+13
2002.355 52404.5 -7.9012e+13  1.4629e+13 -5.2096e+13  9.5569e+12 -1.0628e+14  1.4067e+13 -5.8988e+13  8.1268e+12 -1.2498e+13  9.8725e+12 -
7.3314e+13  1.1800e+13 -1.2662e+14  1.7516e+13 -6.1628e+13  1.0035e+13 -9.1993e+12  5.9916e+12 -1.4778e+13  9.1360e+12  8.9033e+12  6.3605e+12
-8.4012e+13  1.4084e+13  6.3735e+13  1.6391e+13  4.8730e+13  1.3989e+13  4.0267e+13  9.3549e+12 -1.5404e+13  5.5530e+12 -5.2098e+13  1.7664e+13
-1.4040e+14  6.6116e+12 -4.0690e+13  5.5367e+12  2.2929e+14  7.3725e+12  3.9919e+14  9.5656e+12  3.1572e+14  8.6005e+12  5.4816e+13  5.5585e+12
4.5963e+13  8.4020e+12 -7.7725e+12  8.1936e+12  2.1750e+14  1.2020e+13  2.5569e+14  1.8390e+13 -5.0528e+14  6.6378e+13  7.3890e+14  2.7032e+13
4.8931e+14  8.4383e+13
2002.623 52502.5 -8.4828e+13  1.4629e+13 -3.2631e+13  9.5569e+12 -1.0056e+14  1.4067e+13 -7.6653e+13  8.1268e+12 -5.1022e+12  9.8725e+12 -
7.5953e+13  1.1800e+13 -9.2916e+13  1.7516e+13 -7.4375e+13  1.0035e+13 -2.1641e+12  5.9916e+12 -3.3274e+13  9.1360e+12  7.0411e+12  6.3605e+12
-6.5938e+13  1.4084e+13  5.8222e+13  1.6391e+13  9.1261e+13  1.3989e+13  1.0621e+13  9.3549e+12 -1.8149e+13  5.5530e+12 -3.7872e+13  1.7664e+13
-1.4254e+14  6.6116e+12 -3.1735e+13  5.5367e+12  2.2641e+14  7.3725e+12  3.9304e+14  9.5656e+12  3.0173e+14  8.6005e+12  5.2784e+13  5.5585e+12
3.1805e+13  8.4020e+12 -5.6885e+12  8.1936e+12  1.7449e+14  1.2020e+13  2.0061e+14  1.8390e+13 -4.4844e+14  6.6378e+13  7.1485e+14  2.7032e+13
4.6702e+14  8.4383e+13
```

Mass balance estimates are also provided as ASCII tables (*AIS_GMB_trend.dat*). Every line of the file holds all information for a single drainage basin. This includes the region, the mass balance estimate (dmdt), the overall uncertainty (sigma_dmdt), the trend in GIA used to correct the mass change time series prior to the mass balance estimation, the basin area (m^2), the corresponding sea level change rate (dsldt) and its uncertainty (sigma_dsldt). The format is the following:

'region' 'dmdt' 'sigma_dmdt' 'GIA' `area´ `dsldt´ `sigma_dsldt´

All metadata as well as a description of the file format and the units are included in the file header (lines starting with "#"). A sample of the ASCII file is given below (truncated after basin 3):

```
# title: ESA CCI AIS Gravimetric Mass Balance Basin Product
# institution: TU Dresden, Chair of Geodetic Earth System Research
# project: Climate Change Initiative - European Space Agency
# source: GRACE/GRACE-FO L2 monthly solutions provided by Center for Space Research (CSR RL06)
# summary: Linear trends (mass balance) inferred from GRACE/GRACE-FO-derived time series of basin-averaged Antarctic ice mass changes using a linear, periodic (1 year, 1/2 year) and quadratic model
# gia_model: GIA correction: IJ05_R2 (https://doi.org/10.1002/jgrb.50208)
# regions: Regions 1-24,27: drainage basins according to Zwally et al. (2012, http://icesat4.gsfc.nasa.gov/cryo_data/ant_grn_drainage_systems.php), 28: Northern Peninsula, 29: Antarctic Peninsula, 30: East Antarctica, 31: West Antarctica, 32: Antarctic Ice Sheet
# reference: AIS_cci Product User Guide (https://climate.esa.int/en/projects/ice-sheets-antarctic/key-documents/)
# time_coverage_start: 2002-04-18
# time_coverage_end: 2020-07-16
# product_version: 3.0
# date_created: 2021-02-26
# creator_name: Andreas Groh, Martin Horwath
# creator_url: https://tu-dresden.de/bu/umwelt/geo/ipg/gef
# creator_email: martin.horwath@tu-dresden.de
#
# dmdt: trend in ice mass change (ice mass balance)
# sigma_dmdt: overall dmdt uncertainty
# gia: trend in GIA used to correct the mass change time series prior to the mass balance estimation
# area: region area
# dsldt: sea level change rate
# sigma_dsldt: dslsdt uncertainty
# region, dmdt [kg/yr], sigma_dmdt [kg/yr], gia [kg/yr], area (m^2), dsldt [m/yr], sigma_dsldt [m/yr]
AIS01  6.1727e+12  5.7075e+12  1.0405e+13     488594317577 -1.71e-05  1.59e-05
AIS02  3.1363e+12  4.4919e+12  2.1410e+12     791927581921 -8.71e-06  1.25e-05
AIS03  1.5145e+13  1.4073e+13  8.6868e+11   1582904968440 -4.21e-05  3.91e-05
```

All data sets of the GMB basin product (i.e., mass change time series and mass balance estimates) are also available in a single netCDF-4 classic file following the CF conventions in version 1.7. An overview of all variables, dimensions, units, and global attributes is given by the following netCDF header information (ncdump –h):

```
netcdf AIS_GMB_basin {

dimensions:
      time = 187 ;
      strl = 5 ;
      reg = 30 ;
variables:
      double time(time) ;
                time:long_name = "modified julian date" ;
                time:standard_name = "time" ;
                time:units = "days since 1858-11-17 00:00:00" ;
                time:actual_range = 52382., 59046.5 ;
                time:axis = "T" ;
      double time_dec(time) ;
                time_dec:long_name = "decimal year" ;
                time_dec:units = "year" ;
                time_dec:actual_range = 2002.29295003422, 2020.54072553046 ;
      char regions(reg, strl) ;
                regions:long_name = "regions of the Antarctic Ice Sheet" ;
      double area(reg) ;
                area:long_name = "area of the ice sheet regions" ;
                area:standard_name = "grounded_ice_sheet_area" ;
                area:units = "m^2" ;
                area:actual_range = 52267868956., 12308770732500. ;
      double dm(reg, time) ;
                dm:_FillValue = NaN ;
                dm:long_name = "change in ice mass" ;
                dm:units = "kg" ;
                dm:actual_range = -1.4188e+15, 765980000000000. ;
      double sigma_dm(reg, time) ;
                sigma_dm:_FillValue = NaN ;
                sigma_dm:long_name = "uncertainty of the change in ice mass" ;
                sigma_dm:units = "kg" ;
                sigma_dm:actual_range = 5536700000000., 84383000000000. ;
      double dmdt(reg) ;
```

```
                dmdt:_FillValue = NaN ;
                dmdt:long_name = "trend in ice mass change" ;
                dmdt:units = "kg/yr" ;
                dmdt:actual_range = -131340000000000., 64830000000000. ;
        double sigma_dmdt(reg) ;
                sigma_dmdt:_FillValue = NaN ;
                sigma_dmdt:long_name = "uncertainty of the trend in ice mass change" ;
            sigma_dmdt:units = "kg/yr" ;
                sigma_dmdt:actual_range = 748420000000., 43530000000000. ;
        double gia(reg) ;
                gia:_FillValue = NaN ;
                gia:long_name = "trend in GIA applied as correction" ;
                gia:units = "kg/yr" ;
                gia:actual_range = 56480000000., 51499000000000. ;
        double dsldt(reg) ;
                dsldt:_FillValue = NaN ;
                dsldt:long_name = "trend in global average sea level change" ;
                dsldt:standard_name = "tendency_of_global_average_sea_level_change" ;
                dsldt:units = "m/yr" ;
                dsldt:actual_range = -0.00018, 0.
                dsldt:actual_range = -0.00018, 0.000365 ;
        double sigma_dsldt(reg) ;
                sigma_dsldt:_FillValue = NaN ;
                sigma_dsldt:long_name = "uncertainty of the trend in global average sea level change" ;
                sigma_dsldt:standard_name = "tendency_of_global_average_sea_level_change standard_error" ;
                sigma_dsldt:units = "m/yr" ;
                sigma_dsldt:actual_range = 2.08e-06, 0.000121 ;


// global attributes:
                :title = "ESA CCI AIS Gravimetric Mass Balance Basin Product" ;
                :institution = "TU Dresden, Chair of Geodetic Earth System Research" ;
                :source = "GRACE/GRACE-FO L2 monthly solutions provided by Center for Space Research (CSR RL06)" ;
                :history = "2021-02-26: version 3.0 tracking_id 7d6b8d07-5bf3-4089-bd04-877a7a363381, " ;
                :references = "AIS_cci Product User Guide (https://climate.esa.int/en/projects/ice-sheets-antarctic/key-documents/)" ;
                :tracking_id = "7d6b8d07-5bf3-4089-bd04-877a7a363381" ;
                :Conventions = "CF-1.7" ;
                :netCDF_version = "netCDF-4_classic" ;
                :product_version = "3.0" ;
                :format_version = "CCI Data Standards v2.2" ;
                :summary = "GRACE/GRACE-FO-derived time series of basin-averaged Antarctic ice mass changes with respect to the mass as of
2011-01-01 according to a linear, periodic (periods: 1 year, 1/2 year) and quadratic model fitted to the monthly solutions in the period 2002-
08 - 2016-08. Linear trends in ice mass change and the corresponding change in global average sea level are derived from each basin mass change
time series." ;
                :error_estimates = "Provided error estimates of the monthly mass change estimates solely account for the white noise component.
Systematic errors (e.g. errors in the GIA correction) are included in the error estimates of the derived linear trends." ;
                :gia_model = "GIA correction: IJ05_R2 (https://doi.org/10.1002/jgrb.50208)" ;
                :regions = "Regions 1-24,27: drainage basins according to Zwally et al. (2012,
http://icesat4.gsfc.nasa.gov/cryo_data/ant_grn_drainage_systems.php), 28: Northern Peninsula, 29: Antarctic Peninsula, 30: East Antarctica,
31: West Antarctica, 32: Antarctic Ice Sheet" ;
                :keywords = "ESA CCI, Antarctica, Ice Sheet Mass Balance, GRACE, GRACE-FO" ;
                :id = "20210226-ESACCI-AIS-L4-GMB-BASIN-fv3.0.nc" ;
                :naming_authority = "tu-dresden.de/bu/umwelt/geo/ipg/gef" ;
                :keyword_vocabulary = "GCMD" ;
                :cdm_data_type = "Point" ;
                :date_created = "2021-02-26" ;
                :creator_name = "Andreas Groh, Martin Horwath" ;
                :creator_url = "https://tu-dresden.de/bu/umwelt/geo/ipg/gef" ;
                :creator_email = "martin.horwath@tu-dresden.de" ;
                :project = "Climate Change Initiative - European Space Agency" ;
                :geospatial_lat_min = "-90" ;
                :geospatial_lat_max = "-60" ;
                :geospatial_lon_min = "-180" ;
                :geospatial_lon_max = "180" ;
                :geospatial_vertical_min = "0" ;
                :geospatial_vertical_max = "0" ;
                :time_coverage_start = "2002-04-18" ;
                :time_coverage_end = "2020-07-16" ;
                :time_coverage_duration = "P18Y04M" ;
                :time_coverage_resolution = "P1M" ;
                :standard_name_vocabulary = "CF Standard Name Table v77" ;
                :license = "ESA CCI Data Policy: free and open access" ;
                :platform = "GRACE, GRACE-FO" ;
            :sensor = "KBR, ACC, GPS" ;
                :spatial_resolution = "basin scale, data resolution: ~350km" ;
                :key_variables = "change_in_land_ice" ;
}
```

5.3 Product Grid and Projection

The map projection utilized for the GMB gridded product agrees with the projection prescribed for all AIS_cci data products. A polar stereographic projection with reference latitude at 71°S, reference meridian at 0°, and based on the ellipsoid WGS84 (EPSG:3031) is used.

5.4 Product Flags and Metadata

For the GMB gridded product a fill value of "NaN" is used for all grid cells outside the ice sheet margin. The global attributes of the netCDF and the GeoTIFF file contain additional information on the product, like the sensor used, temporal bounds of the data set, the GIA model used, the product version, and applied conventions. A detailed listing of all metadata is given in Section 5.2.

5.5 Available Software Tools

Tools for extracting data and reading metadata from netCDF files as well as libraries for a wide range of programming languages are freely available from Unidata (http://www.unidata.ucar.edu/software/netcdf). Additionally, the website gives a detailed overview on free software packages supporting the netCDF format.

The GeoTIFF files can be viewed and browsed using any Geographic Information System (GIS). QGIS is a freely available open-source GIS software package (http://www.qgis.org).

5.6 References

Bettadpur, S. (2018). GRACE UTCSR Level-2 Processing Standards Document for Level-2 Product Release 0006, v5.0; Technical Report; Center for Space Research, The University of Texas at Austin: Austin, TX, USA.

Groh, A.; Horwath, M.; Horvath, A.; Meister, R.; Sørensen, L.S.; Barletta, V.R.; Forsberg, R.; Wouters, B.; Ditmar, P.; Ran, J.; Klees, R.; Su, X.; Shang, K.; Guo, J.; Shum, C.K.; Schrama, E.; Shepherd, A (2019). Evaluating GRACE Mass Change Time Series for the Antarctic and Greenland Ice Sheet—Methods and Results. Geosciences, 9, 415. doi:10.3390/geosciences9100415.

Groh, A.; Horwath, M (2021). Antarctic Ice Mass Change Products from GRACE/GRACE-FO Using Tailored Sensitivity Kernels. Remote Sens., 13, 1736. doi:10.3390/rs13091736.

Ivins, E. R., James, T. S., Wahr, J., O. Schrama, E. J., Landerer, F. W., & Simon, K. M. (2013). Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. J. Geophys. Res. Solid Earth, 118(6), 3126–3141.

Save, H. (2019). GRACE-FO CSR Level-2 Processing Standards Document for Level-2 Product Release 06, v1.1. Technical Report; Center for Space Research, The University of Texas at Austin: Austin, TX, USA.

6 Ice Shelf CoastLine (ISCL) Products

NOTE: This section of the ADP was written as a result of CCN1 of ESA contract number 4000143397/23/I-NB.

This chapter describes the Ice Shelf CoastLine (ISCL) ECV parameter products.

The objective of the proposed activity is to investigate the added benefits of combining radar measurements (Sentinel-1) with altimetry (CS2) in the delineation of ice shelf coastlines. This investigation will be conducted over three selected ice shelves (Larsen-C, Ronne, Filchner). Those three ice shelves cover a large area and have been subject to large calving events in the recent past. Furthermore, they represent challenging areas with the simultaneous presence of glaciers and islands.

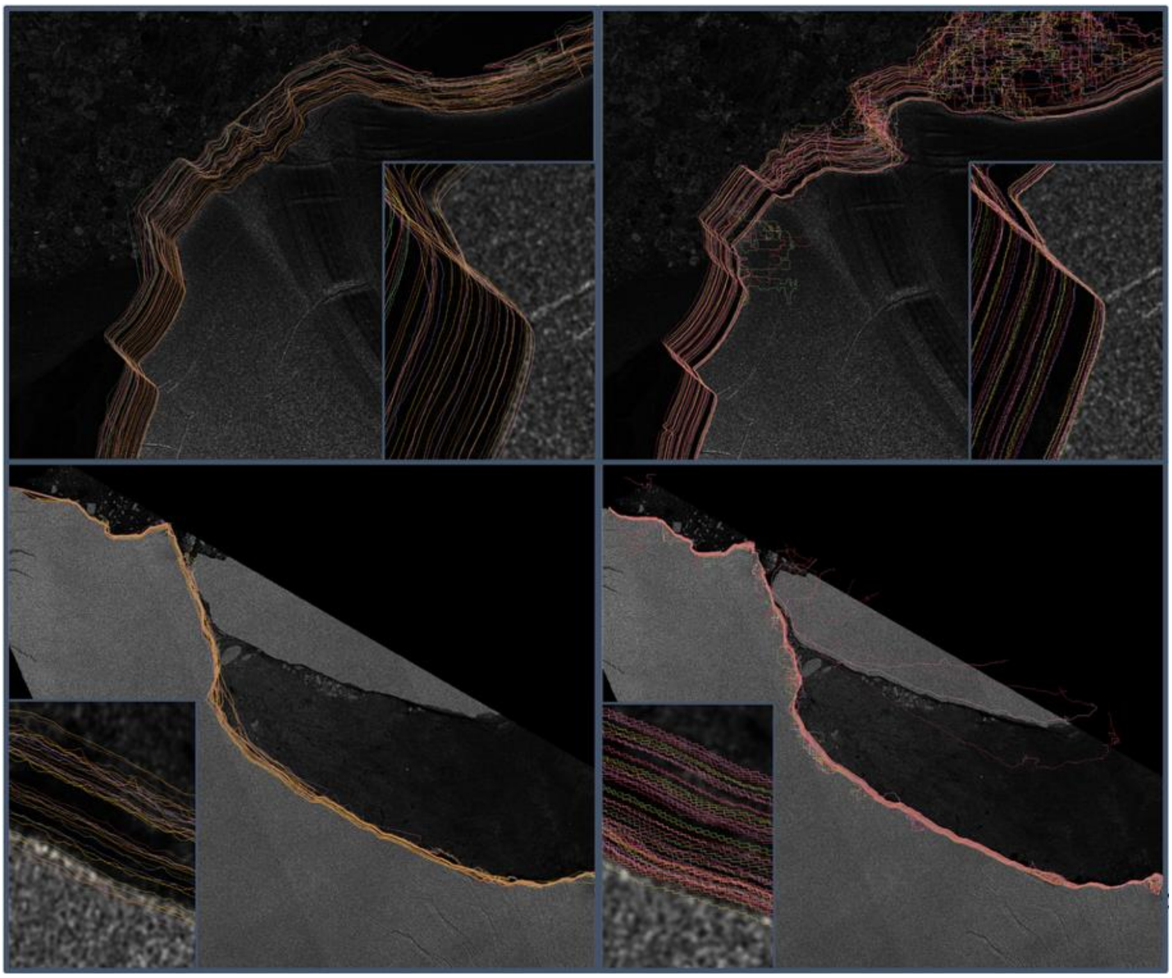


Figure 6.1: ISCL monthly products for Filchner and LarsenC (left) in comparison to the IceLines products by Baumhoer et. al.

Delineation of the Ice Shelf CoastLine (ISCL) will be performed using both SAR images from Sentinel-1 and elevation data from CryoSat-2 altimetry tracks. The elevation data compiled from CS2 tracks will provide an initial guess for the model based on elevation differences that can indicate the start of the ice shelf coastline. That initial guess along with corresponding SAR imagery from the designated time and location from Sentinel-1 will be fed to a Convolutional Neural Network (CNN) That will combine the 2 inputs to predict a first iteration of the location of the ISCL. Then, the model will be run iteratively as a refinement network to refine the prediction until the location converges to the predicted ISCL.

6.1 Product Geophysical Data Content

The products will be in the form of GeoPackage vector data (.gpkg) for easy distribution, opening, and size requirements. Each file will contain a line string which holds the data of the line in EPSG:32720 CRS. The name of the file indicates the month it corresponds to, while the folder indicates the year. For example, in the LarsenC folder, 4 other folders will be found corresponding to each year, then inside each one, 12 files will be named after each month. The data extends from 2018 to 2022 across the LarsenC, Ronne(1 and 2) and Filchner ice shelves. It has a spatial resolution dependent on the S1 image mode used. Since we are using GRD images, it can reach 20 x 22 for IW and 50 x 50 meters for EW image modes.

6.2 Product Grid and Projection

The data is in vector form, so it doesn't follow a grid based format. It has an EPSG:32720 CRS.

6.3 Product Flags and Metadata

Table 6.1: List of Metadata values

Attribute	**Format Mandatory**	**Attribute description**
ID	int YES	Identification number of the Processing Agency value set to -1 (indicating missing value)
Ice Shelf	varchar(20) YES	Name of the Ice Shelf
time_coverage_start	timestamp YES	Start time of the covered month
time_coverage_end	timestamp YES	End time of the covered month
platform	text YES	Platform/s (Satellite/s) used
project	text YES	ESA Project

Attribute	Format Mandatory	Attribute description
summary	text NO	Summary of the product
analy_time	timestamp YES	Time analysis was done
region	text YES	
data_src	text YES	Description of data source
proc_desc	text YES	Description of processing: e.g. Manual, semi-automatic
inst_name	varchar(80) YES	Instrument name
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
institution	text YES	Developing Institution
history	text YES	Version History
product_version	numeric(11,4) YES	Product Version
orthocorred	char(1) YES	Ortho-corrected: yes (y), no (n)
naming_authority	text YES	Authority naming the product
comment	text NO	General Comment

Table 6.2: Naming Convention

Part	Meaning
ISCL	Ice Shelf Coast Line
<ice_shelf>	Name of the Ice Shelf (Either LarsenC, or Filchner,

	or Ronne1 or Ronne2)
<start_date>	Start date of the month range
<end_date>	End date of the month range

6.4 Available Software Tools

The ISCL product is distributed as Geopkg 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).

6.5 References

Baumhoer CA, Dietz AJ, Heidler K, Kuenzer C. IceLines–A new data set of Antarctic ice shelf front positions. Scientific Data. 2023 Mar 15;10(1):138.

7 Prototype Uplift product from InSAR line-of-sight

7.1 Product Geophysical Data Content

The Line-of-sight Ice Velocity product (LoS-IV) is a prototype product containing timeseries of single-pair Sentinel-1 InSAR displacement rate measurements. The aim of this product is to provide a product with high temporal resolution tailored to study rapidly varying and transient ice uplift/subsidence phenomena, such as those associated with subglacial water transport. Observing such phenomena on ice caps 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,2023). Despite its name, the LoS-IV product actually provides a time series of vertical displacement rate 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,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 rate 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 vertical displacement rate to produce the output variable, called `uplift_rate`.

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

For a given timestamp, the `uplift_rate` is the average change in the ice surface height per day (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. The `TB` variable holds the temporal baseline and can be used to calculate the total uplift between the two acquisitions. An example of an uplift map from the prototype product is shown in Figure 7.1

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

```
v_los [m/d]= los_velocity_time_median + uplift_rate*sin(los_elevation_angle)
```

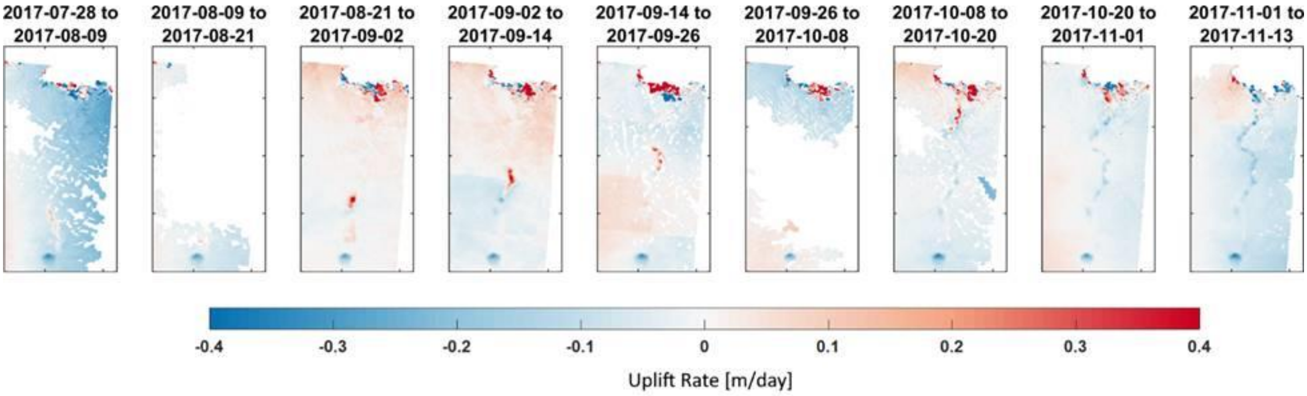


Figure 7.1: Example uplift rate maps from different timestamps from the product, showing a persistent subsidence signal at the bottom, and an uplift signal propagating towards the top of the image, leaving a trail of subsidence. This is interpreted as a subglacial lake draining, with the water traveling towards the coast.

7.2 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 7.1: 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_rate`	float32	m/day	time,y,x	Inferred vertical displacement rate 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.

1.

7.3 File naming convention

The NetCDF files are named in the following way:

`antarctica_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):

```
antarctica_uplift_s1_qml_t102a_20170728_20250123.nc
```

This name indicates data from Queen Maud Land (QML) acquired from track 102 (ascending) with the timeseries starting at 2017-07-28 and ending 2025-01-23.

7.4 Product Grid and Projection

The selected map projection for all the Antarctic Ice Sheets CCI data products is Antarctic polar stereographic with a reference latitude at 71S, a reference meridian at 0W, and using the ellipsoid WGS84 [PSD].

7.5 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 artifacts 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 localized 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 kind 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.

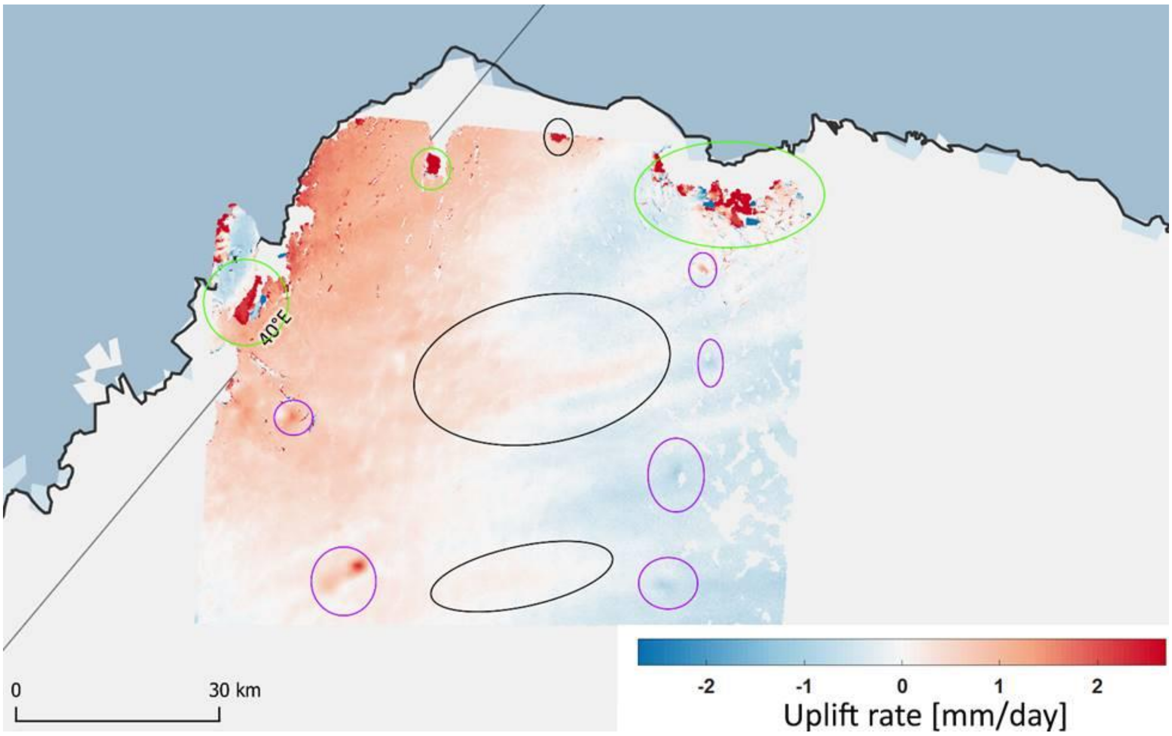


Figure 7.2: Uplift map with examples of typical signals and errors from the QML product (2018-09-15). The areas in the magenta ellipses we interpret as real geophysical signals (subsidence/uplift), whereas areas in green ellipses contain phase unwrapping artifacts, characterized by a sharp delineation to the surroundings. The black ellipses indicate typical atmospheric error signals. The linear gradient from the left to the right side of the image is typically the result of a calibration error, and likely not caused by surface displacement.

7.6 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 free and open-source solution. To view the uplift timeseries, the QGIS plugin "Raster Timeseries Manager" can be installed.

7.7 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

8 How to Obtain the Data Products

The data products are accessed via the following options:

- Partner Portals
- CCI Data Portal

8.1 Partner Portal Access

Links to the three Partner Portals are provided on the AIS_cci project website (https://climate.esa.int/en/projects/ice-sheets-antarctic/data/).

8.1.1 SEC from UK CPOM Data Portal

SEC products are provided as part of the UK CPOM Data Portal (https://www.cpom.ucl.ac.uk/csopr/).

The CPOM data portal provides a set of operational cryosphere earth observation data products which include Antarctic SEC products (from the ESA CCI and CPOM research output), near real time sea ice thickness and Antarctic ice sheet velocity. All CPOM portal sites provide additional user-friendly functions to visualise product maps and climate variable time series. Full access to SEC CCI product downloads is available following a simple user registration step and site login (Figure 8-3).

Figure 8-1: CPOM Data Portal home page.

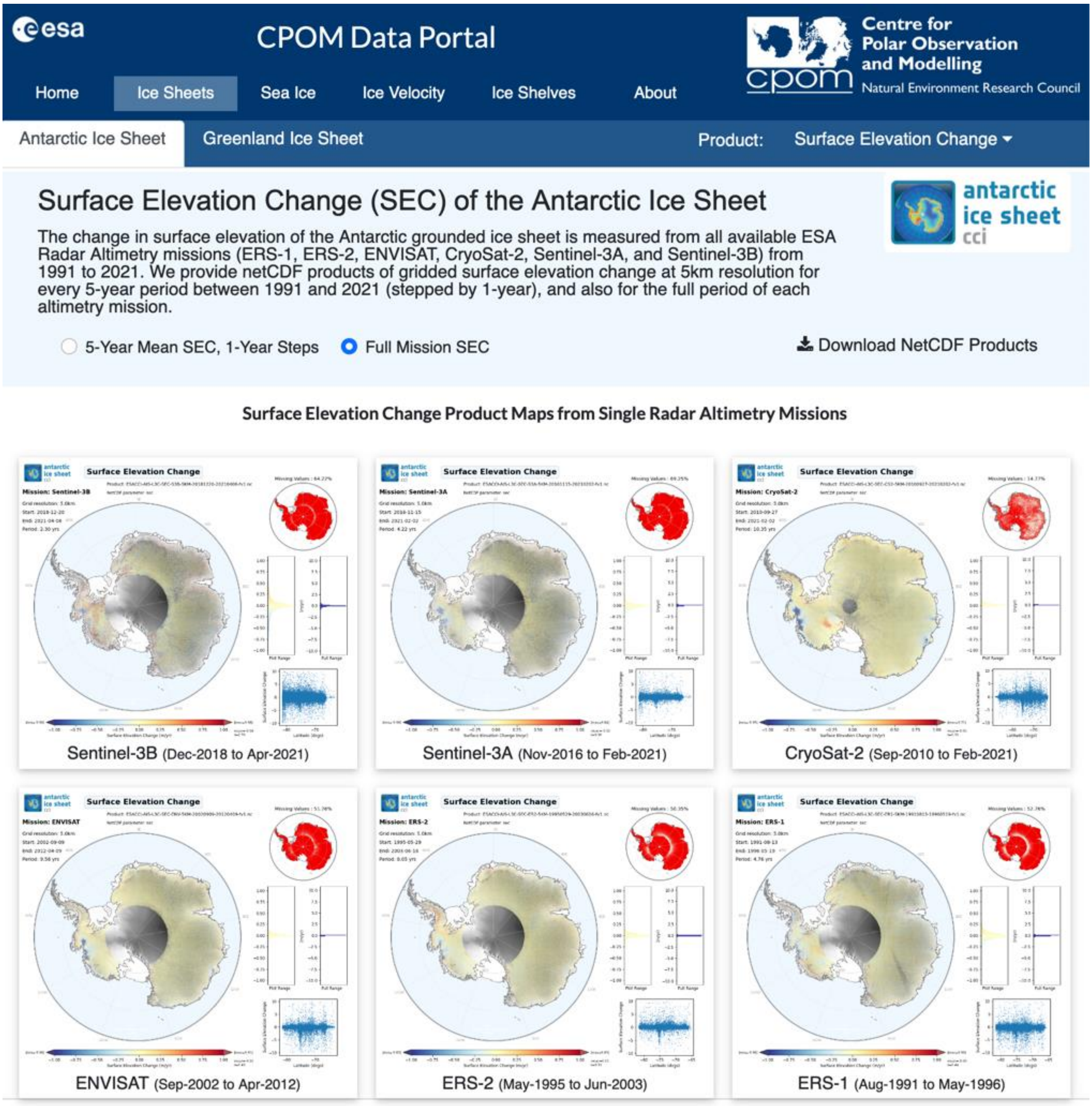


Figure 8-2: The Antarctic SEC portal.

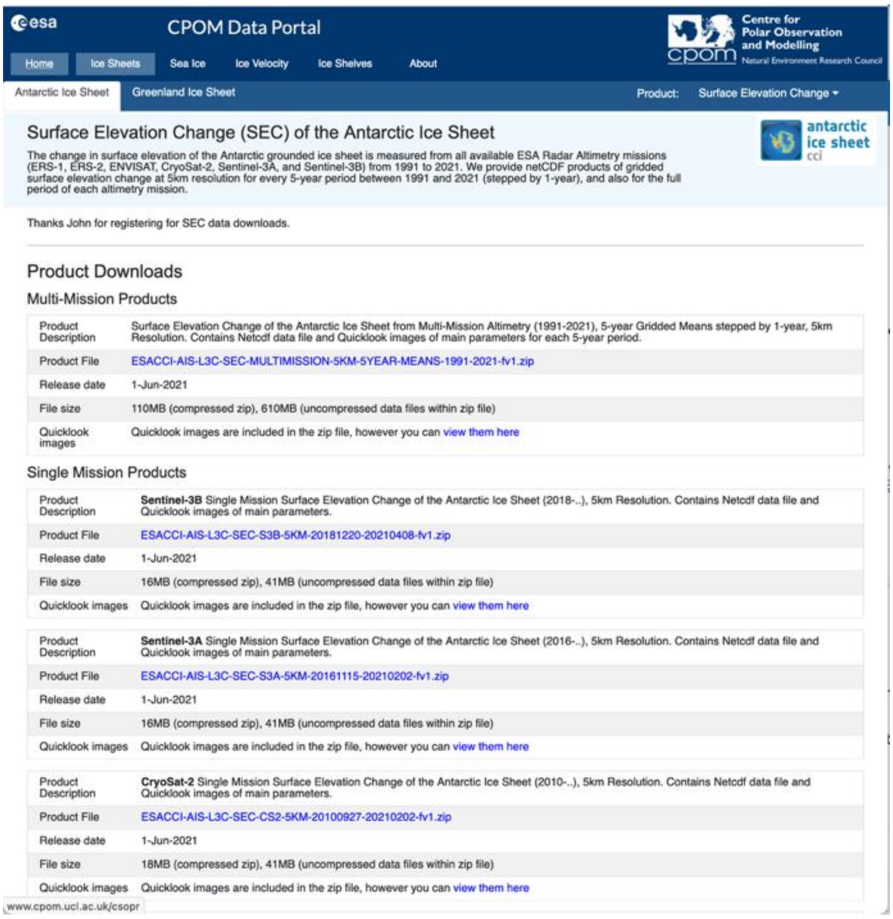


Figure 8-3: Data download from the Antarctic SEC portal.

8.1.2 IV and GLL from ENVEO CryoPortal

CryoPortal (http://cryoportal.enveo.at/) is operated by ENVEO and provides free access to cryospheric products and services from satellite data for Antarctica and Greenland, as well as various ice caps and glaciers (Figure 8-4). Products are generated by ENVEO and partners within projects funded by ESA, FFG/BMVIT, European Commission and others. The data portal can be used for browsing, distributing, downloading and simple analysis of data products (e.g., IV profile generation along glacier center lines, mass flux analysis etc.). To get full access to services and download capability of products requires registration and login. There are different user levels (anonymous, external, partner & staff) that determine the permissions for reading and accessing the data. These can be adjusted for each product individually. Currently it is possible to download IV and GLL products generated for AIS_cci by ENVEO and DLR respectively.

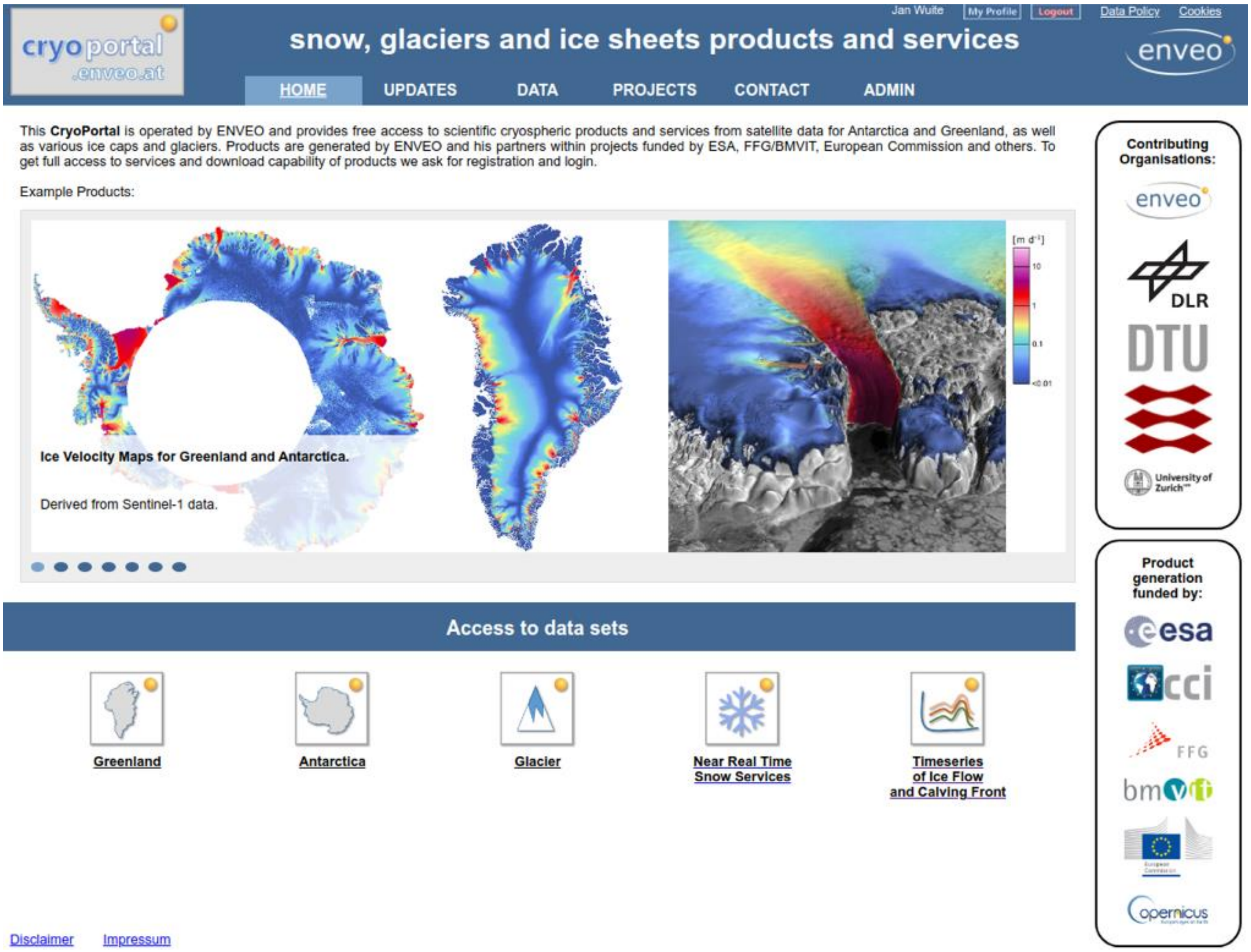


Figure 8-4: ENVEO CryoPortal homepage.

8.1.3 GMB from TUDr Data Portal

The Gravimetric Mass Balance (GMB) products are freely available from a data portal hosted by TU Dresden (https://data1.geo.tu-dresden.de/ais_gmb/). The site offers user-friendly, interactive browsing and exploring of both the GMB basin and the GMB gridded product.

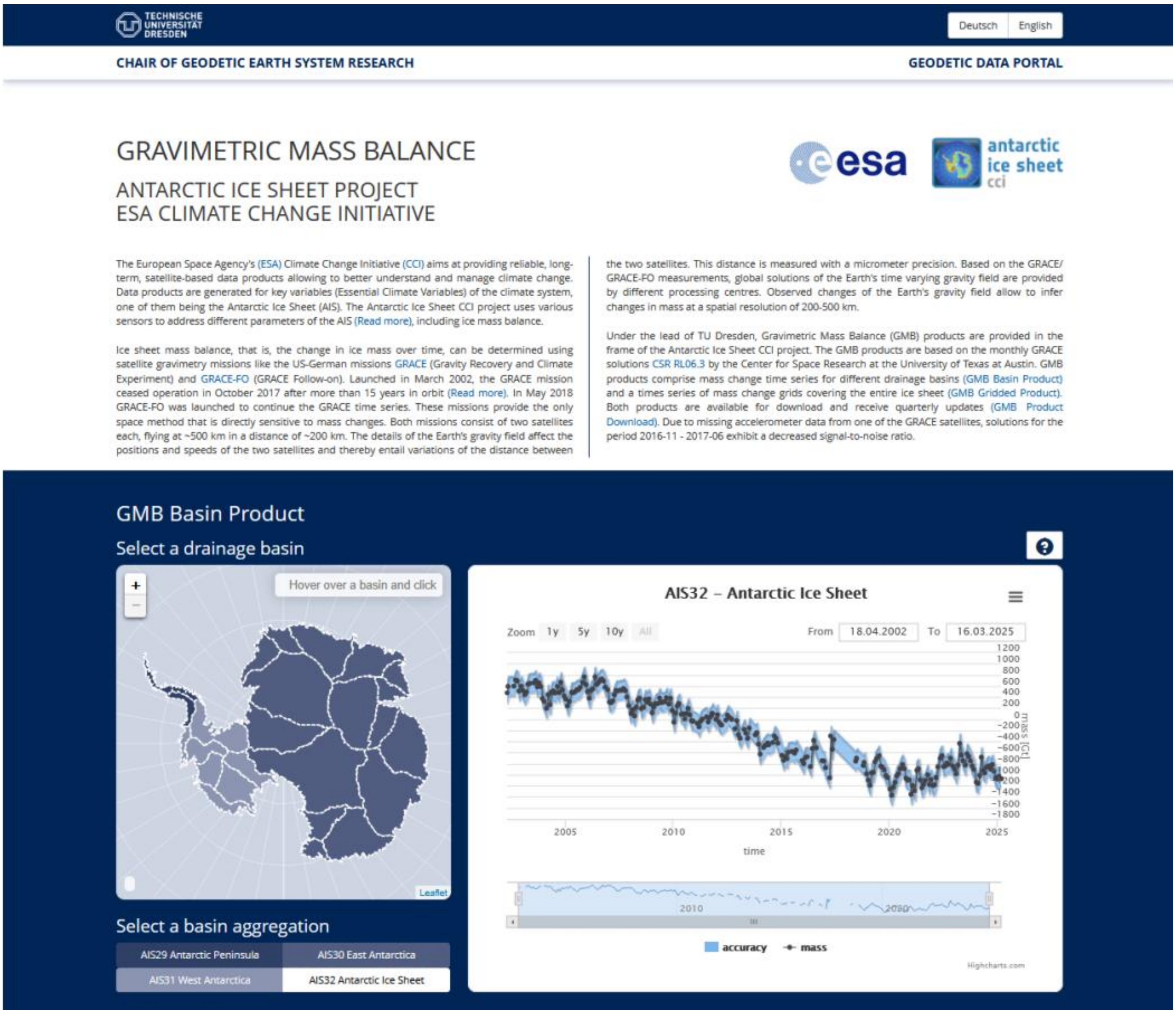


Figure 8-5: Home page of the GMB data portal and the GMB basin product page showing the ice mass time series for the entire Antarctic Ice Sheet.

Mass change time series for individual drainage basins can be displayed by selecting the basin of interest from a map (Figure 8-5). The time series plot allows to zoom to a certain period and to query values for a specific monthly solution. The plot can be saved in raster (png) and vector (svg) format.

An animation of the monthly grid series is available to visualise the GMB gridded product. By selecting a particular month from the plot of the mass change time series for the entire AIS, the corresponding monthly grid is displayed.

Before downloading one of the data sets provided, at the bottom of the page, the user needs to enter his personal details. Downloading the data implies the user's promise to cite the data set whenever results based on the GMB products are published.

8.2 CCI Open Data Portal Access

ESA collects data products published by all CCI projects on a central, common website, the CCI Open Data Portal (ODP, https://climate.esa.int/en/odp) (Figure 8-6), from where users have access to products published by all ESA CCI projects.

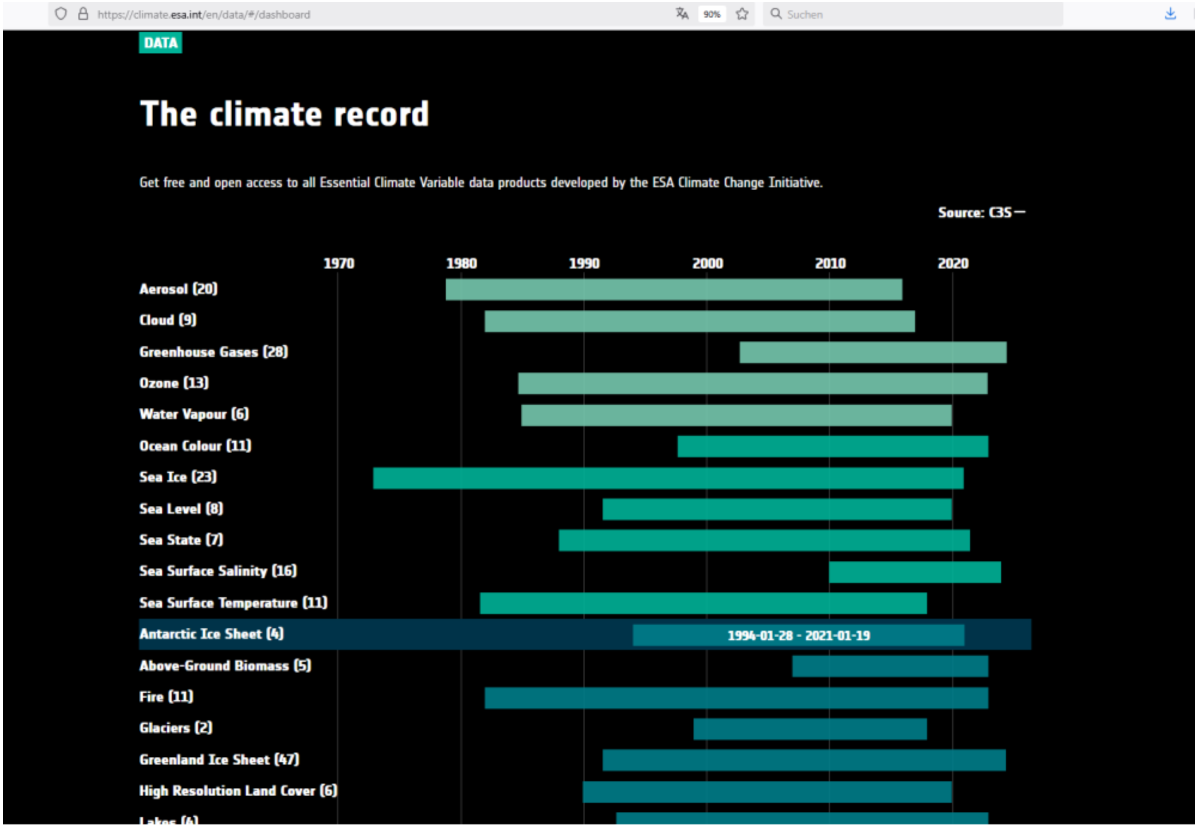


Figure 8-6: CCI Open Data Portal home page

The ODP is updated at irregular intervals with the products published on the Partner Portals. Clicking on “Antarctic Ice Sheet” will display the available AIS_cci products. Selecting a product and then clicking the link “Dataset” on the right-hand side will open the corresponding product record in the CEDA Data Catalogue, hosted by the Centre for Environmental Data Analysis (UK).