CryoTEMPO-EOLIS
Elevation Over Land Ice from Swath
Product Handbook

Land Ice Elevation Thematic Point Product

Land Ice Elevation Thematic Gridded Product

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Approval

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Document Versions

Issue	Date	Doc ID	Reason for change
1.0	10th October 2019	CS_CTS_PHB_EWAVE_0100	First version of document
1.1	25th April 2020	CS_CTS_PHB_EWAVE_0101	Revisions for first release
1.2	11th October 2020	CS_CTS_PHB_EWAVE_0102	Added Antarctica
2.0	22nd November 2021	CS_CTS_PHB_EWAVE_0200	Added Glacier regions
3.0	15th March 2023	CS_CTS_PHB_EWAVE_0300	Updated for EOLIS Baseline 2
3.1	22nd January 2024	CS_CTS_PHB_EWAVE_0301	Updated for the release of new products
3.2	13th May 2023	CS_CTS_PHB_EWAVE_0302	Updated to include the new Antarctic Ice Shelves product

Contents

List of acronyms

CRS	Coordinate Reference System
DEM	Digital Elevation Model
EO	Earth Observation
EOLIS	Elevation Over Land Ice from Swath
ESA	European Space Agency
FTP	file transfer protocol
GDAL	Geospatial Data Abstraction Library
GS	Ground Segment
InSAR	Interferometric Synthetic Aperture Radar
LRM	Low Resolution Mode of the CryoSat-2 radar sensor
NetCDF	Network Common Data Form (binary file format)
OIB	Operation Ice Bridge
PDGS	Payload Download Ground Segment
POCA	Point-Of-Closest-Approach
SARIn	The CryoSat-2 SAR Interferometry mode
STSE	Science, Technology, Society and Environment education
UoE	University of Edinburgh
UTC	Coordinated Universal Time
XML	Extensible Mark-up Language

1. Introduction

1.1 Scientific Background

CryoSat-2's primary mission objectives are to monitor the changes affecting the world's sea and land ice to quantify thickness, mass trends, and the contribution to sea-level change. In practice, CryoSat's revolutionary interferometric design has allowed several technical breakthroughs and led to the application of radar altimetry to environments that were previously unforeseen. One such breakthrough is Swath processing of CryoSat's SARIn mode, making full exploitation of the information contained in CryoSat's waveforms and leading to one to two orders of magnitude more measurements than the conventional so-called POCA technique.

Following on from the early demonstration of the technique and its potential impact, the "CryoSat ThEMatic PrOducts - SWATH Cryo-TEMPO" project (CryoTEMPO-EOLIS) aims to consolidate the research and development undertaken during the CryoSat+ CryoTop / CryoTop evolution ESA STSE projects (Gourmelen et al., 2018),the CryoSat+ Mountain Glaciers project (Foresta et al., 2016; Foresta et al., 2018; Jakob L. et al., 2021; Jakob & Gourmelen, 2023) and Polar+ Ice Shelves project (Gourmelen et al., 2017; Davison et al., 2023) into operational products. The purpose of the thematic products is to make the data available to the wider scientific community in a form that does not require a detailed understanding of the sensor used and extensive post-processing. The CryoTEMPO-EOLIS consists of two distinct products:

1) a point product, containing a cloud of elevations with an associated uncertainty in geospatial units;

2) a gridded product, containing a spatial interpolation of the point product onto a uniform grid of elevation and uncertainty.

This Product Handbook describes the operational products, which provide analysis-ready data to a wider community of scientists rather than altimetry experts.

The ***CryoTEMPO-EOLIS Algorithm Technical Baseline Document (ATBD)*** (https://cryotempo-eolis.org/cryotempo_eolis_thematic_product_atbd_latest) contains more detailed descriptions of the algorithms outlined in this document.

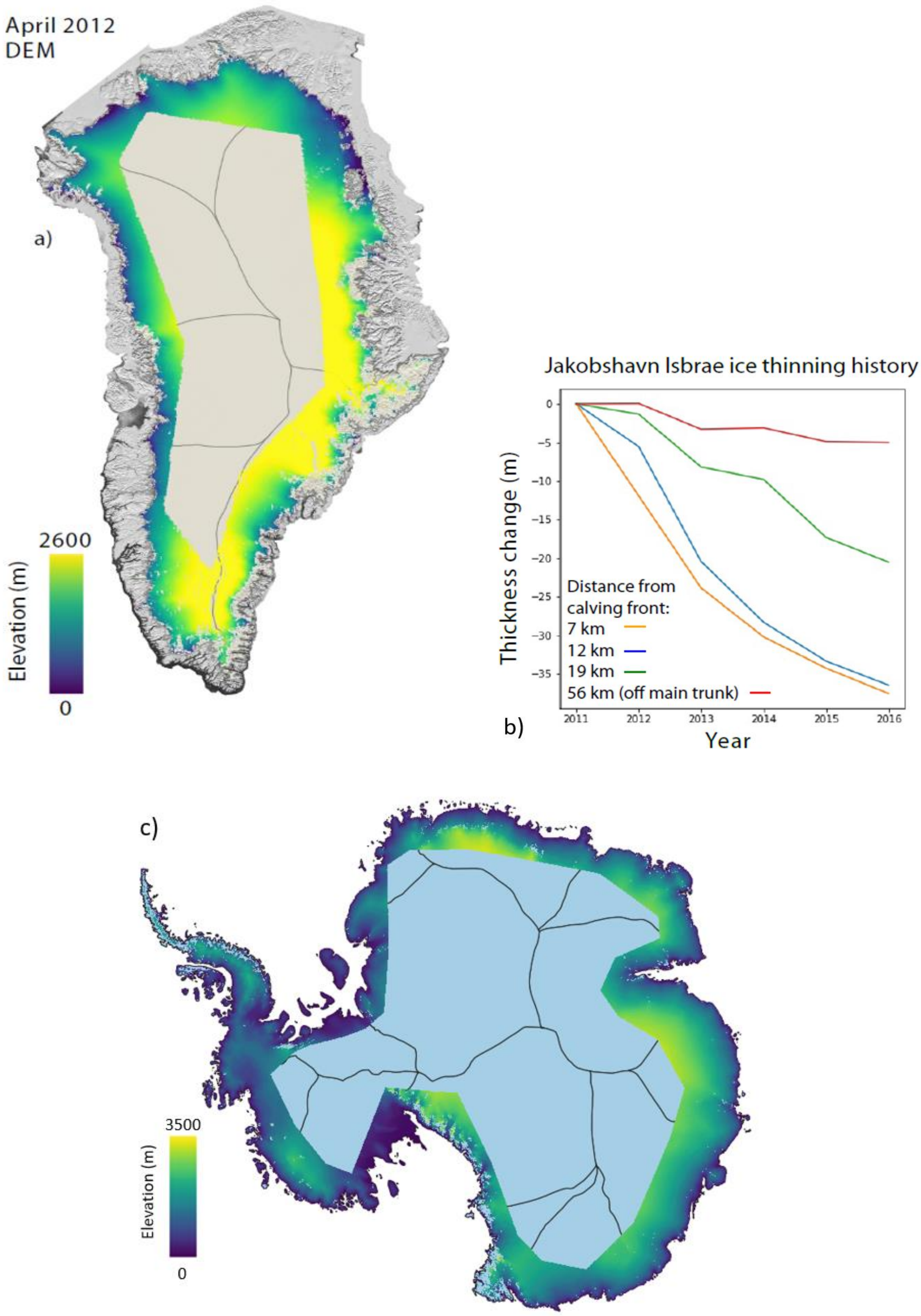

Figure 1: a) Example EOLIS digital elevation model of the Greenland Ice Sheet, overlayed on the MODIS Greenland dataset and drainage basins (Gourmelen et al., 2018; Haran et al., 2018; Shepherd et al., 2020) ; b) Ice thinning history using time-series of CryoTEMPO-EOLIS digital elevation models near to the Jakobshavn Isbrae Glacier; c) Example EOLIS digital elevation model of the Antarctica Ice Sheet overlayed on the drainage basins.

1.2 Product Access

The products are published to the ESA science server and are downloaded via an FTP client. Details of how to log in to the FTP can be found on ESAs CryoSat products page at https://earth.esa.int/eogateway/catalog/cryosat-products. The FTP server is located at: ftp://science-pds.cryosat.esa.int/. The point and gridded products are stored in the TEMPO_SWATH_POINT and TEMPO_SWATH_GRID directories respectively. As described in Section 3.1.3, a shapefile file containing a mosaic of the point product is available in the TEMPO_SWATH_POINT directory.

Additionally, CryoTEMPO-EOLIS products can be downloaded via the altimetry portal https://cs2eo.org/. This service allows for interactive visualisation of available CryoTEMPO-EOLIS data. Useful features include queries using a bounding box or drawn polygons, custom temporal querying, and immediate visualisation of the spatial coverage of query result. Moreover, https://cs2eo.org/timeseries can be used to explore and download time series of elevation change, which can be quickly calculated for custom-drawn polygons using the CryoTEMPO-EOLIS gridded products.

For further information about the CryoTEMPO-EOLIS products, please see the project website: https://cryotempo-eolis.org/.

Besides general information about the product access, the website provides interactive tutorials that enable quick and simple access to either the point or gridded products, and show examples of the kinds of analysis that are possible. These tutorials run in Jupyter Notebooks via the Google Colab interface and can be accessed and run by anyone with a Google account, and no knowledge or experience of python programming is required. The tutorials can be found at https://cryotempo-eolis.org/tutorials/.

1.3 Product Citation

The recommended citation for the EOLIS products is as follows.

Data over glaciers:

"EOLIS elevation data generated using swath processing of CryoSat-2 data (Jakob & Gourmelen, 2023) and provided by the ESA CryoTEMPO project (https://cryotempo-eolis.org/)."

Jakob, L., and Gourmelen, N., (2023). Glacier Mass Loss Between 2010 and 2020 Dominated by Atmospheric Forcing. Geophysical Research Letters 50(8), 1-10. https://doi.org/10.1029/2023GL102954

Data over ice sheets and ice shelves:

"EOLIS elevation data generated using swath processing of CryoSat-2 data (Gourmelen et al., 2018) and provided by the ESA CryoTEMPO project (https://cryotempo-eolis.org/)."

Gourmelen, N., Escorihuela, M., Shepherd, A., Foresta, L., Muir, A., Garcia-Mondejar, A., Roca, M., Baker, S., & Drinkwater, M. R. (2018). CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change. Advances in Space Research 62(6), 1226-1242. https://doi.org/10.1016/j.asr.2017.11.014

1.4 Versioning

The chapters below describe the processing of Baseline 2 of the CryoTEMPO-EOLIS products. When a new version of the products is released, you will be informed via the https://cryotempo-eolis.org/ website. The version number indicated in the product filename will be incremented. Both the current (Baseline 2) and previous (Baseline 1) versions of the CryoTEMPO-EOLIS products are available to access via the ESA Science Server (see Section 3).

1.5 Contacts

Feedback or questions about the CryoTEMPO-EOLIS Thematic Products is welcomed. Please use the following contact details:

e-mail: support@cryotempo-eolis.org | *Website:* http://www.cryotempo-eolis.org

1.6 Reference Websites

CryoTOP Evolution: https://cryotop-evolution.org/

ESA CryoSat-2 Data Download: https://science-pds.cryosat.esa.int/

Arctic DEM: https://www.pgc.umn.edu/data/arcticdem/

REMA DEM: https://www.pgc.umn.edu/data/rema/

Gapless-REMA100: https://figshare.com/articles/dataset/Gapless-REMA100/19122212

TanDEM-X: https://earth.esa.int/web/eoportal/satellite-missions/t/tandem-x

SRTM DEM: https://srtm.csi.cgiar.org/

Copernicus DEM Data Download: https://registry.opendata.aws/copernicus-dem

CryoSat+ Mountain Glaciers: https://www.cryosat-mtg.org/

ICESat-2: https://icesat-2.gsfc.nasa.gov/

Randolph Glacier Inventory (RGI) 7.0: https://www.glims.org/RGI/

MEaSUREs BedMachine: https://nsidc.org/data/nsidc-0756/versions/3

Polar+Iceshelves: https://polar-iceshelf.org

2. Product Details

2.1 Coordinate System & Geographic Projection

Vertical datum: the elevation in EOLIS is measured with respect to the WGS84 ellipsoid.

Projections for each of the EOLIS product regions are detailed in Table 1.

Table 1: Regional Projections

Region		EPSG Code	Proj4 Code
Greenland Ice Sheet/Periphery		3413	"+proj=stere +lat_0=90 +lat_ts=70 +lon_0=-45 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs"
Antarctica Ice Sheet/Periphery/Ice Shelves		3031	"+proj=stere +lat_0=-90 +lat_ts=-71 +lon_0=0 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs"
Alaska		3413	"+proj=stere +lat_0=90 +lat_ts=70 +lon_0=-45 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs"
Western Canada & USA		N/A	"+proj=tcea +lon_0=-119.5 +datum=WGS84 +units=m +no_defs"
Arctic Canada North/South		3413	"+proj=stere +lat_0=90 +lat_ts=70 +lon_0=-45 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs"
Iceland		3413	"+proj=stere +lat_0=90 +lat_ts=70 +lon_0=-45 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs"
Svalbard		3413	"+proj=stere +lat_0=90 +lat_ts=70 +lon_0=-45 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs"
Scandinavia / Central Europe		3035	"+proj=laea +lat_0=52 +lon_0=10 +x_0=4321000 +y_0=3210000 +ellps=GRS80 +towgs84=0,0,0,0,0,0,0 +units=m +no_defs +type=crs"
Russian Arctic		3413	"+proj=stere +lat_0=90 +lat_ts=70 +lon_0=-45 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs"
Central/South East/South West Asia		4326	"+proj=longlat +ellps=WGS84 +datum=WGS84 +no_defs"
Low Latitudes		N/A	"+proj=tcea +lon_0=-73 +datum=WGS84 +units=m +no_defs"
Southern Andes	Point product	4326	"+proj=longlat +ellps=WGS84 +datum=WGS84 +no_defs"
	Gridded product	32719	"+proj=utm +zone=19 +south +datum=WGS84 +units=m +no_defs"
New Zealand		N/A	"+proj=tcea +lon_0=172.5 +datum=WGS84 +units=m +no_defs"

2.2 Geographic Extent

The CryoTEMPO-EOLIS product is available only over the CryoSat-2 SARin zone (the SARin mask is available here: https://earth.esa.int/web/guest/-/geographical-mode-mask-7107, date accessed: 13th March 2023).

The product uses the following masks for the two ice sheets, the Antarctic Ice Shelves and the glacier regions:

1) For the Greenland Ice Sheet and the Antarctic Ice Sheet the drainage basins masks charted in the Rignot data set are used (Rignot et al., 2011).
2) For the Antarctic Ice Shelves, the floating ice mask as defined by MEaSUREs BedMachine (v3) is used (Morlighem M. , 2022; Morlighem et al., 2020)
3) The glacier regions use the Randolph Glacier Inventory (RGI) 7.0 masks (RGI 7.0 Consortium, 2023)

Product coverage is illustrated in Figure *2*. Further detail of the regions covered by the CryoTEMPO-EOLIS point and gridded products is provided in Sections 2.3.2 and 2.4.2 respectively.

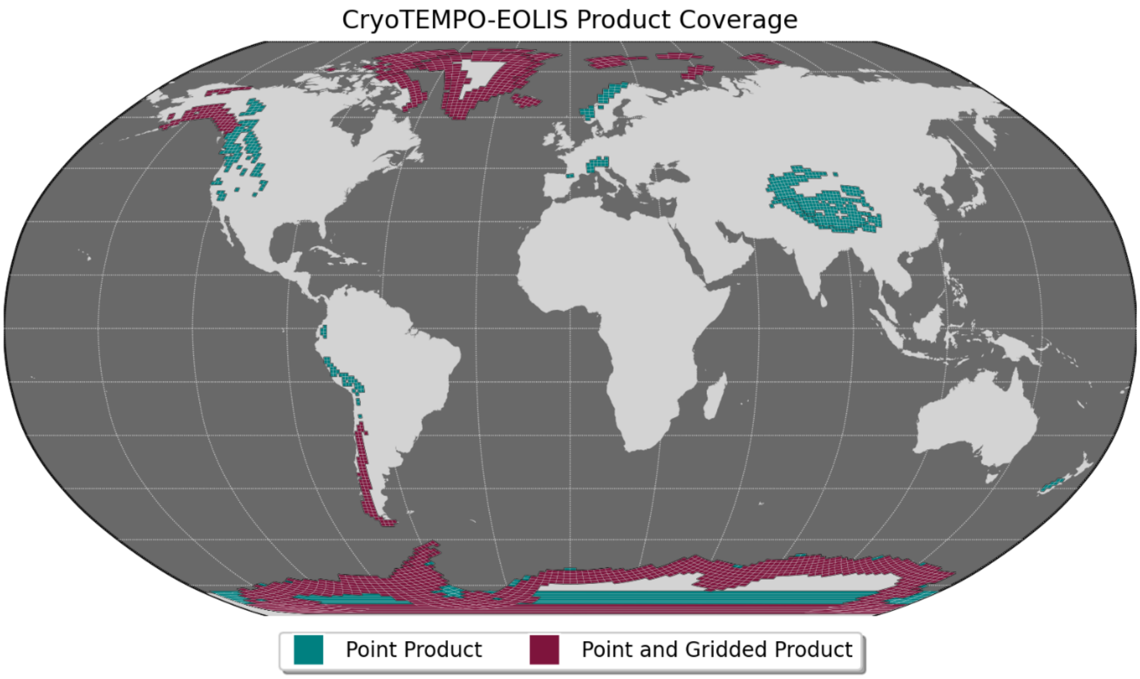

Figure 2: CryoTEMPO-EOLIS product coverage.

2.3 Thematic Point Product Overview

The CryoTEMPO-EOLIS point product is a set of high-quality CryoSat-2 swath altimetry point data. It is published for 20 regions (see section 2.3.2), in each case providing a monthly elevation dataset with associated uncertainties in geospatial units.

This product is designed to be user-friendly; for use by non-altimetry experts. Due to the high volume of data, the monthly product is split spatially into tiles of 100 x 100 km.

2.3.1 Point Product Uncertainty Score

The CryoTEMPO-EOLIS Quality Control is a critical process applied to guarantee that the products use only the most accurate altimeter data. A quality flag is generated for each elevation point. Only high-quality points are used in the Thematic Point and Gridded products.

Published point products contain elevation measurements with associated uncertainties, in units of meters. To assign uncertainty scores to each swath point, an uncertainty look-up table is generated. For this, a subset of the swath elevation points is binned into a six-dimensional array using all combinations of 6 swath quality variables. In each bin the uncertainty is calculated as the 95th percentile of the standard deviation of the elevation differences to an auxiliary altimetry dataset.

2.3.2 Point Product Spatial Coverage

The CryoTEMPO-EOLIS point product is published in 100 x 100 km tiles. These tiles are shown for all regions in Figure 3 to Figure 5; the projections of these figures do not reflect the projection of the products themselves.

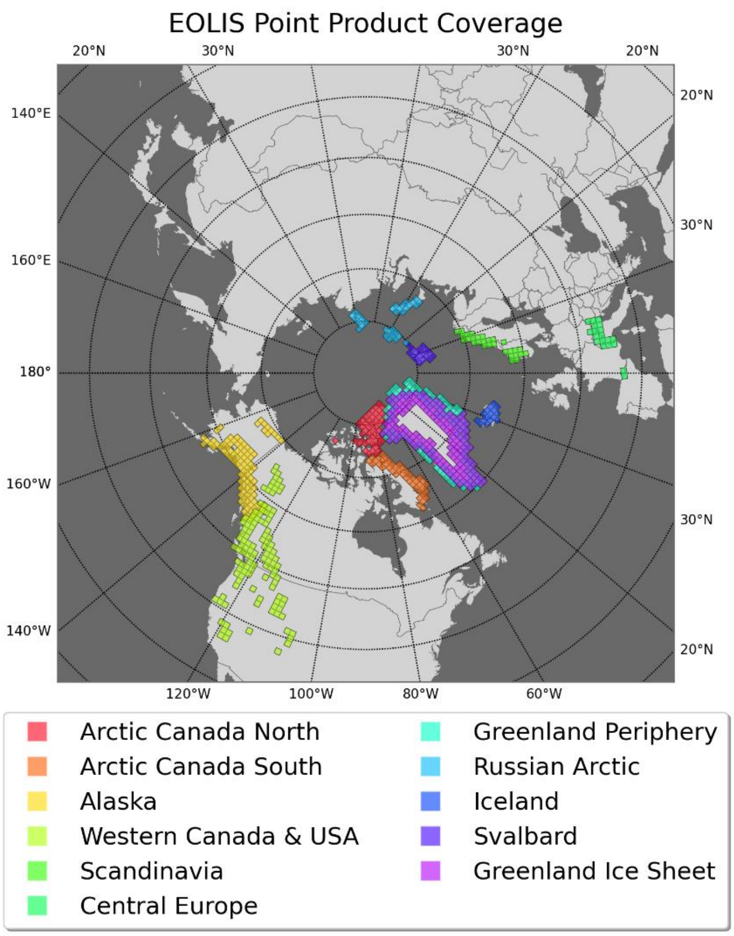

Figure 3: CryoTEMPO-EOLIS point product coverage for products in the Northern Hemisphere. Tiles are 100 x 100 km.

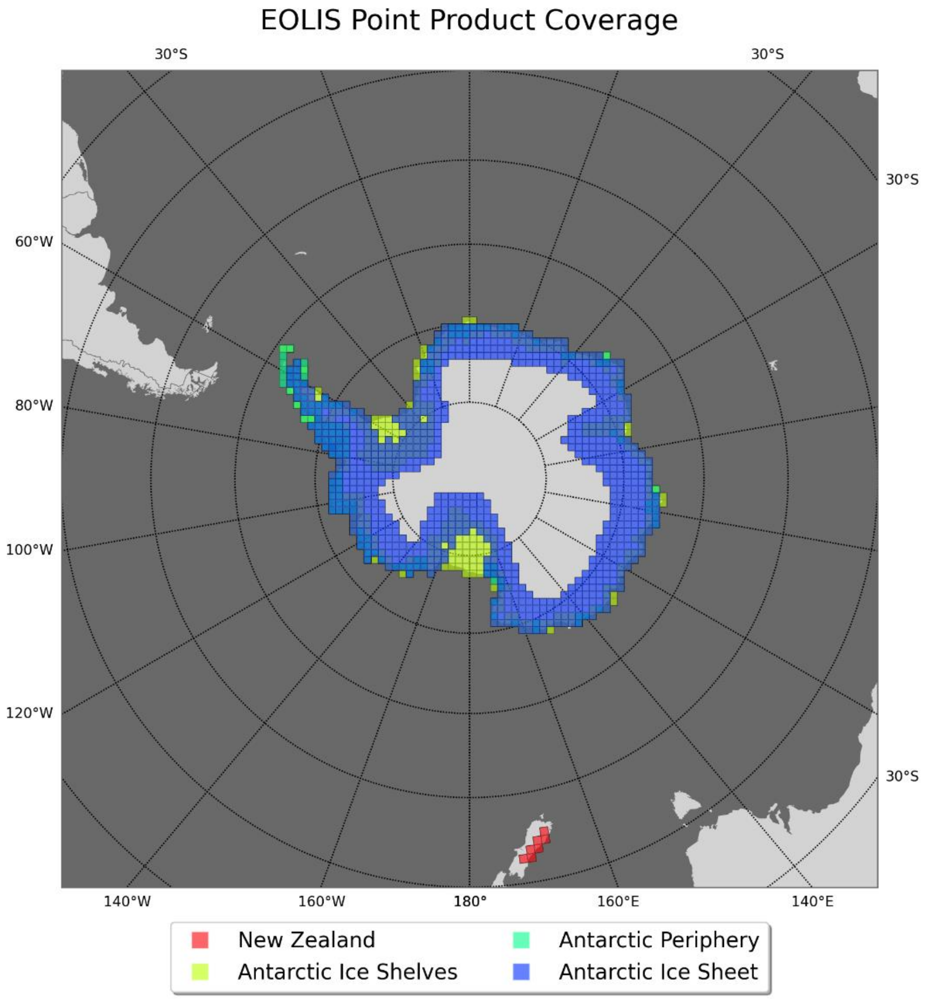

Figure 4: CryoTEMPO-EOLIS point product coverage for regions in and around the Antarctic. Tiles are 100 x 100km.

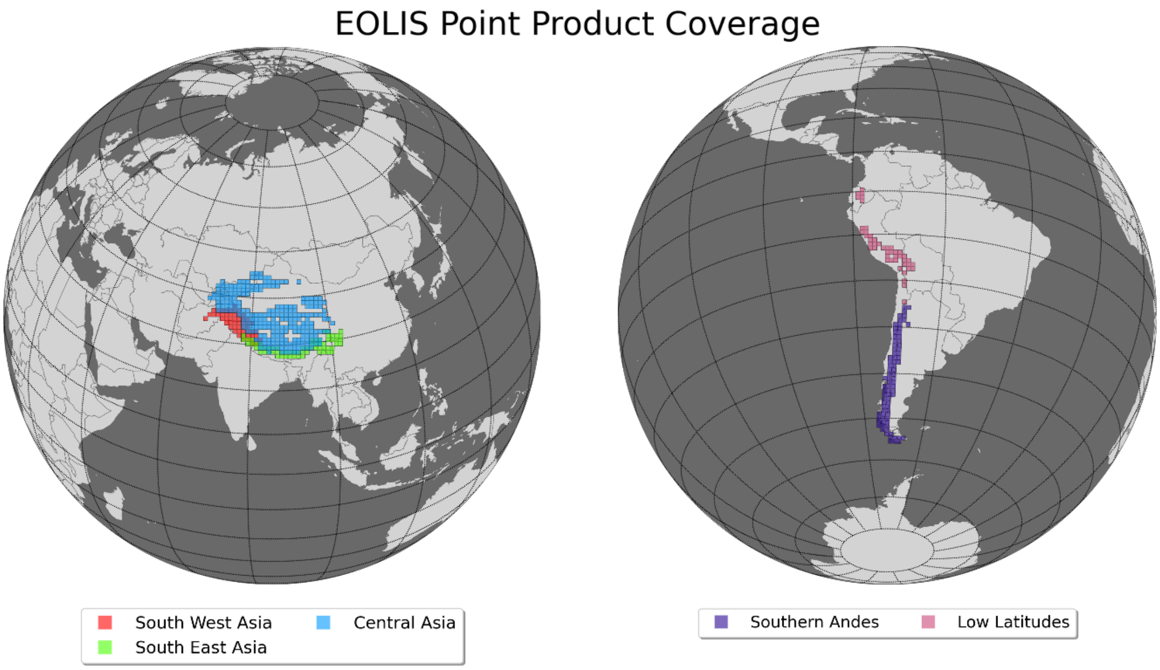

Figure 5: CryoTEMPO-EOLIS point product coverage closer to the equator. Tiles are 100 x 100 km.

2.3.3 Point Product Temporal Coverage

Baseline 2 – Currently in operation

All regions, except for Western Canada & USA, Scandinavia, Central Europe, Low Latitudes, New Zealand and Antarctic Ice Shelves, have monthly data available from July 2010. Data for Western Canada & USA, Scandinavia, Central Europe, Low Latitudes and New Zealand is available from December 2023. Data for Antarctic Ice Shelves is available from April 2024. The data from July 2010 for these regions will be available once the back processing has been completed.

Baseline 1 – No longer in operation

Point products are available from July 2010 for the Greenland and Antarctic Ice Sheets, from July 2021 for Iceland, Svalbard, Canadian Arctic, Russian Arctic, Alaska, and Southern Andes, and from October 2021 for regions in Asia. Data is available up to December 2022. After this date, CryoTEMPO-EOLIS Baseline 1 was retired from operations, and as such, no new data will be available.

2.4 Thematic Gridded Product

CryoTEMPO-EOLIS gridded products are produced for the following geographic regions:

- Greenland Ice Sheet
- Antarctic Ice Sheet
- Alaska
- Arctic Canada North
- Arctic Canada South
- Greenland periphery
- Iceland
- Svalbard
- Russian Arctic
- Southern Andes
- Antarctic periphery

The gridded product is published on a monthly basis on a 2 km grid in polar stereographic coordinates.

The monthly product contains 3 months of data on a rolling basis each month and uses the Thematic point product as its input. For example, the January 2023 gridded product will contain point data for a window starting on 1st December 2022 and ending on 28th February 2023. Details of the temporal window can be found in the HDR file for each product (see section 3.3.3).

2.4.1 Gridded Product Uncertainty Score

Each pixel of the gridded product has an uncertainty associated with its elevation value, in units of meters. These gridded uncertainties are derived from the point uncertainty, which is propagated by taking spatial autocorrelation into account for each region. The coefficients for calculating spatial autocorrelations are generated for each region separately with a semi-variogram.

2.4.2 Gridded Product Spatial Coverage

Spatial coverage of all CryoTEMPO-EOLIS gridded products is the same as for the point product detailed in section 2.3.2.

2.4.3 Gridded Product Temporal Coverage

Baseline 2 – Currently in operation

Gridded products are available from August 2010 for the Greenland and Antarctic Ice Sheets. All other gridded regions have monthly data available from November 2023 immediately, and then will be back processed to August 2010.

Baseline 1 – No longer in operation

Gridded products are available from August 2010 for the Greenland and Antarctic Ice Sheets, and from August 2021 for Iceland and Svalbard. Data is available up to November 2022. After this date, CryoTEMPO-EOLIS Baseline 1 was retired from operations, and as such, no new data will be available.

3. Data Format

3.1 Nomenclature

There are 2 files for each instance of a data product:

- XML HDR file that contains detailed product metadata,
- e.g. *CS_OFFL_THEM_POINT_ARCCANNOR_2023_01_-1000000__-1100000__V201.HDR*
    - This follows the specification: "EO GS File Format Standard", with small modifications to refer to polar coordinates rather than longitude and latitude.
- NetCDF data file that contains the point cloud and gridded products respectively, e.g. *CS_OFFL_THEM_POINT_ARCCANNOR_2023_01_-1000000__-1100000__V201.nc*

3.1.1 Point Product Nomenclature

Each CryoTEMPO-EOLIS TEMPO_SWATH_POINT product consists of a pair of files:

- a header file (with extension .HDR) in XML format.
- a data block file (with extension .nc) in netCDF format.

The folder structure on the ESA Science Server is: TEMPO_SWATH_POINT/YYYY/MM/<ZONE>

The file naming convention is:

CS_OFFL_THEM_POINT_<ZONE>_<YYYY>_<MM>_<X>_<Y>_<VERSION>

Where:

- <ZONE> = Fixed number of chars 9 selectable among one of the following:

Table 2: CryoTEMPO-EOLIS product zone names.

Zone Name	**<ZONE>**
Greenland Ice Sheet	GREENLAND
Antarctica Ice Sheet	ANTARCTIC
Antarctic Ice Shelves	ANTICESHF
Alaska	ALASKA___
Western Canada & USA	WESTCANUS
Arctic Canada North	ARCCANNOR
Arctic Canada South	ARCCANSOU
Greenland Periphery	GREENPERI
Iceland	ICELAND__
Svalbard	SVALBARD_
Scandinavia	SCANDINAV
Russian Arctic	RUSSIANAR
Central Europe	CENTRALEU
Central Asia	CENTRASIA
South Asia West	SOUASIAWE
South Asia East	SOUASIAEA
Low Latitudes	LOWLAT___
Southern Andes	SOUTHANDE
New Zealand	NEWZEALND
Antarctic Periphery	ANTARCPER

- <YYYY> = Year in format YYYY (e.g., 2012)
- <MM> = Month in format MM (e.g., 10 for October)
- <X> = Coordinate of the south west corner of the grid (in metres), in format (+/-) XXXXXXXX
- <Y> = Coordinate of the south west corner of the grid (in metres), in format (+/-) XXXXXXXX
- <VERSION> = four characters string VVVV where the first character can be alphanumeric and the remaining 3 numeric. The first numeric character refers to the baseline, and the third numeric character refers to the version of the product (this is incremented if the file is replaced with a newer version).

For example: *CS_OFFL_THEM_POINT_ALASKA____2023_01_-2300000__+300000___V201.nc*

3.1.2 Gridded Product Nomenclature

The gridded product closely follows the nomenclature of the point product. There is a pair of NetCDF and HDR files with the data in the former and the metadata in the latter.

The file naming convention for the gridded product is:
CS_OFFL_THEM_GRID__<ZONE>_<YYYY>_<MM>_<VERSION>

Where <ZONE>, <YYYY>, <MM>, and <VERSION> have the same definitions as set out in Section 3.1.1.

For example: *CS_OFFL_THEM_GRID__GREENLAND_2022_12_V201.nc*

3.1.3 Shapefile Nomenclature

A tar archive containing a shapefile that has the data tiles in a spatial format. The attributes of the file contain the path to the data on the PDGS server.

The naming of the tar archive is as follows:

CS_OFFL_THEM_POINT_<ZONE>_<YYYY>_<MM>.tgz

Where <ZONE>, <YYYY> and <MM> are defined in Section 3.1.1.

For example: *CS_OFFL_THEM_POINT_GREENLAND_2019_05.tgz*

The shapefile format consists of a collection of files(.shp, .shx, .dbf, and .prj), e.g.:

- *CS_OFFL_THEM_POINT_index_GREENLAND_2019_05.shp*
- *CS_OFFL_THEM_POINT_index_GREENLAND_2019_05.prj*
- *CS_OFFL_THEM_POINT_index_GREENLAND_2019_05.shx*
- *CS_OFFL_THEM_POINT_index_GREENLAND_2019_05.dbf*

3.1.4 Previous Baseline Data

Although it is recommended that users use the latest version of the CryoTEMPO-EOLIS products, the previous operational version of CryoTEMPO-EOLIS Baseline 1 data is still available for download from the FTP Server. The Baseline 1 products can be found in the following directories:

TEMPO_SWATH_POINT_Baseline-1

TEMPO_SWATH_GRID_Baseline-1

This location follows the same folder structure and filename conventions as described above for Baseline 2 products.

3.2 Thematic Point Product – Variables & Attributes

3.2.1 Dimensions

The defined dimension is “row”. Each row in the data file represents a spatial temporal point.

3.2.2 Point Product Data Columns

Table 3: CryoTEMPO-EOLIS point product parameter definitions.

Variable Name	Type	Content	Unit
time	Integer32	Number of seconds that have elapsed since January 1, 1970 (midnight UTC/GMT)	Seconds
x	Float32	Spatial position on the x-axis using the projection defined for the region.	Metres
y	Float32	Spatial position on the y-axis using the projection defined for the region.	Metres
elevation	Float32	Elevation of the point in space-time.	Metres
uncertainty	Float32	Quality indicator of the estimated height.	Metres
is_swath	Integer32	Indicates if the observation is from the swath (1) processor or is from ESA's L2 dataset (0).	0,1
input_file_id	Integer32	Identifier of the input L1b and L2 products for swath and POCA respectively.	Numeric ID

For data covering the Southern Andes and Asia, the reference coordinate system used is WGS84, and therefore latitude and longitude coordinates will be provided instead of the x, and y coordinates used in all other regions. These coordinates are in units of degrees.

3.2.3 Point Product NetCDF Metadata

The metadata contains global attributes that reference documentation and variable attributes that describe the content and units of measurement.

The full NetCDF header is provided in Appendix A1. A selection of fields that may be of most interest to users include:

- **geospatial_projection:** this field contains a proj4 string, which describes the projection used to create this product (and corresponds to the region projection given in Table 1).
- **baseline:** the software baseline used to create the products. The current operational CryoTEMPO-EOLIS baseline is '2'.
- **version:** the version of this product file that has been downloaded. This number will be incremented if the file has been replaced with a newer version on the ESA Science Server, and starts from '1'.
- **time_coverage_duration:** this field contains a shorthand for the temporal duration of the product. For point product files it is set to 'P1M', where the integer defines how many months of data the product includes.
- **fileids:** this field contains a list of filenames for each of the individual swath data files that are used to generate the point product.

3.2.4 Point Product HDR files

Each data file has an associated HDR file that is in XML format. The HDR file contains metadata about the product including the spatial extent, the time window of validity, and details about the products that have been used as inputs for the construction of the product.

In the specific header, the product location specifies the spatial area in polar coordinates that the product refers to. The Data Structure Definitions (DSDs) section of the specific header provides the data lineage of the inputs into the TEMPO_SWATH_POINT product. There are both L1B and L2 references because the POCA from the L2 and the swath derived from the L1B product are included.

An example of a point product HDR file is shown in Appendix A2. The following fields from each HDR file may be of particular interest to users:

- **<Product_Location>** tag contains the coordinates of the extent of the product in polar stereographic coordinates.
- **<Proc_Time>** tag gives the timestamp for the creation of each product file.
- **<Data_Set_Descriptor>** tag contains details of each Swath or POCA data file that contributes to the point product.

3.3 Thematic Gridded Product - Variables & Attributes

3.3.1 Dimensions

The gridded product file has 3 dimensions:

- **time**: with a single value corresponding to midnight of the first day of the month.
- **x**: spatial position on the x-axis using the projection defined for the region.
- **y**: spatial position on the y-axis using the projection defined for the region.

3.3.2 Gridded Product Data Columns

Table 4: CryoTEMPO-EOLIS gridded product parameter definitions.

Variable Name	Type	Content	Unit
time	Integer32	Number of seconds that have elapsed since January 1, 1970 (midnight UTC/GMT)	Seconds
x	Float32	Spatial position on the x-axis using the projection defined for the region	Metres
y	Float32	Spatial position on the y-axis using the projection defined for the region	Metres
x_bnds	Float32	The upper and lower bound of x for each pixel	Metres
y_bnds	Float32	The upper and lower bound of y for each pixel	Metres
nv	Integer32	Index of nearest vertex, where 0 is westerly or southerly and 1 is northerly or easterly	0,1
elevation	Float32	Elevation of the point in space-time	Metres
uncertainty	Float32	Quality indicator of the estimated elevation	Metres

3.3.3 Gridded Product NetCDF Metadata

The metadata in the file contains global attributes that reference documentation and variable attributes that describe the content and units of measurement.

The full NetCDF header is provided in Appendix A3. A selection of fields that may be of most interest to users include:

- **time_coverage_duration:** this field describes the temporal coverage of the data used to generate the product. For gridded product files it is set to 'P3M' by default, i.e., 3 months.
- **geospatial_resolution:** the resolution of the gridded products in meters.

3.3.4 Gridded Product HDR Files

The HDR file contains the metadata for the gridded thematic product. An example of a point product HDR file is shown in Appendix A4. Sections that are of particular interest are in the Specific Product Header <SPH>, for example:

- **<Product_Location>** tag contains the coordinates of the extent of the product in polar stereographic coordinates.
- **<Resolution>** pixel height and width in metres.
- **<Interpolation_Window>** - is the time window for which data has been contributed to the product.
- **<Window_Start>** tag contains the UTC when the first swath and POCA products are included.
- **<Window_End>** tag contains the time of the last data contribution.
- **<Window_Centre>** publication date that the product is effective for.

3.4 Data Format Differences Between Baseline 1 & Baseline 2

There are some minor differences between the metadata and product variable names of EOLIS Baseline 1 and Baseline 2 data.

For users wishing to work with data from the previous baseline, the following differences should be noted:

NetCDF Metadata:

- 'product_version': this Baseline 1 metadata field refers to the baseline used to create the product (this field was renamed 'baseline' in Baseline 2).
- No 'region' parameter was provided in Baseline 1.

Point Product Variables;

- The 'is_swath' parameter is named 'isSwath' in Baseline 1 products.
- The 'input_file_id' variable is named 'inputfileid' in Baseline 1 products

4. Improvements From Previous Baseline

There are several significant improvements in the CryoTEMPO-EOLIS baseline 2 products. These include swath processing advancements such as waveform filtering and a more robust phase model adjustment, which together result in an increase in data quality and volume across all product regions. Additionally, gridding algorithms for the Greenland ice sheet and the Antarctic ice sheet have been updated to use the same algorithm that was used in the baseline 1 gridded products for Iceland and Svalbard. This gridding algorithm reduces noise and increases coverage compared to the baseline 1 gridded product as well as newly providing a gridded uncertainty. Filtering of POCA data in the point products has been revised to remove points where the POCA retracker has failed.

This section will detail some of the observed improvements in the CryoTEMPO-EOLIS baseline 2 products compared to baseline 1.

4.1 Coverage

The CryoTEMPO-EOLIS Baseline 2 products show an overall increase in coverage across all gridded regions. Coverage of the two ice sheets has improved dramatically, in particular around the ice sheet periphery (see Figure 6).

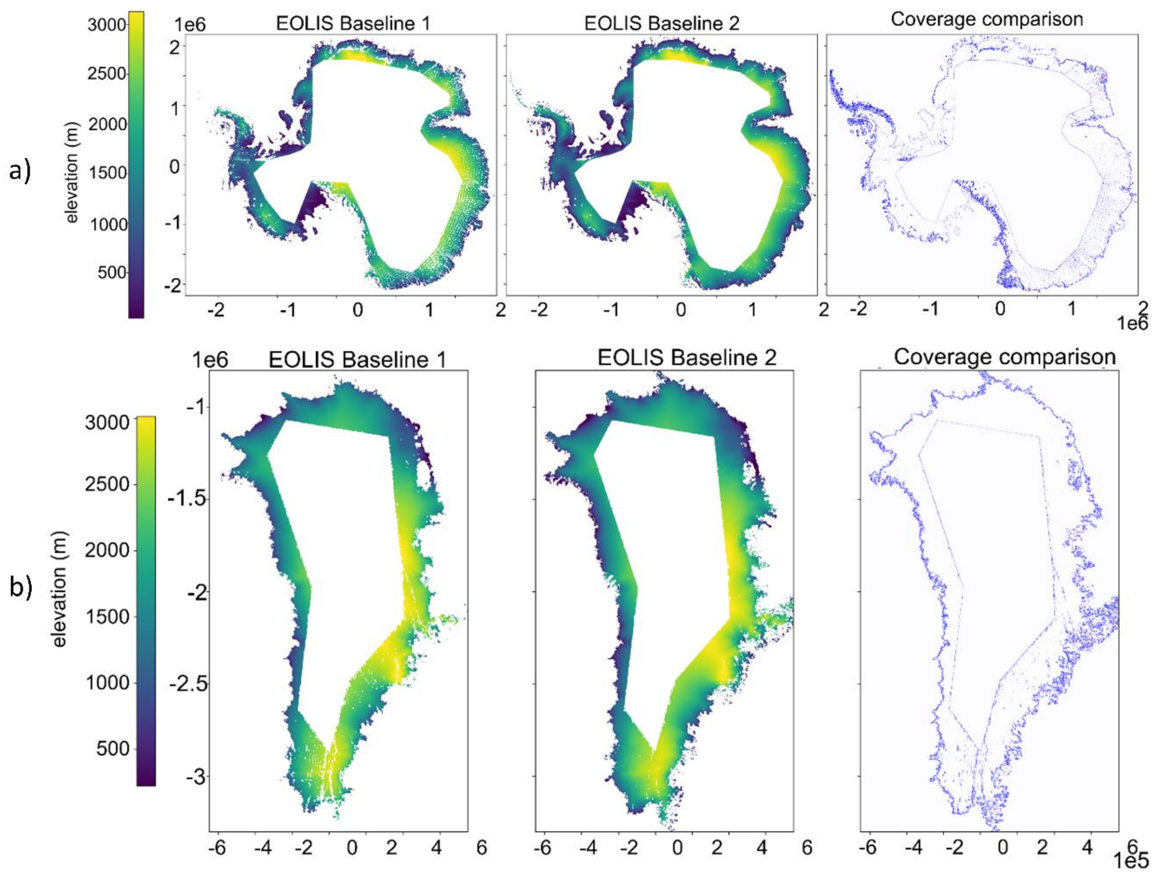

Figure 6: Improvement in coverage over a) the Antarctic Ice Sheet and b) the Greenland Ice Sheet between EOLIS Baseline 1 and 2. Left: EOLIS Baseline 1 gridded product for February 2019. Middle: EOLIS Baseline 2 gridded product for February. 2019. Right: Coverage change between the two baselines: blue = gain of coverage from Baseline 1 to 2, red = loss of coverage from Baseline 1 to 2.

4.2 Data Volume

CryoTEMPO-EOLIS baseline 2 boasts a significant data volume increase compared to baseline 1 products due to increased data quality (see Figure 7). The Greenland Ice Sheet and the Antarctic Ice Sheet have a volume gain of 42% and 60% respectively, largely due to the improved phase model adjustment (see Section 5.3). Data volume in Asia has also increased significantly due to an algorithm change which removes the reliance on POCA for each swath waveform. Additionally, data volume for all other glacier regions has increased in the range of 5-14%.

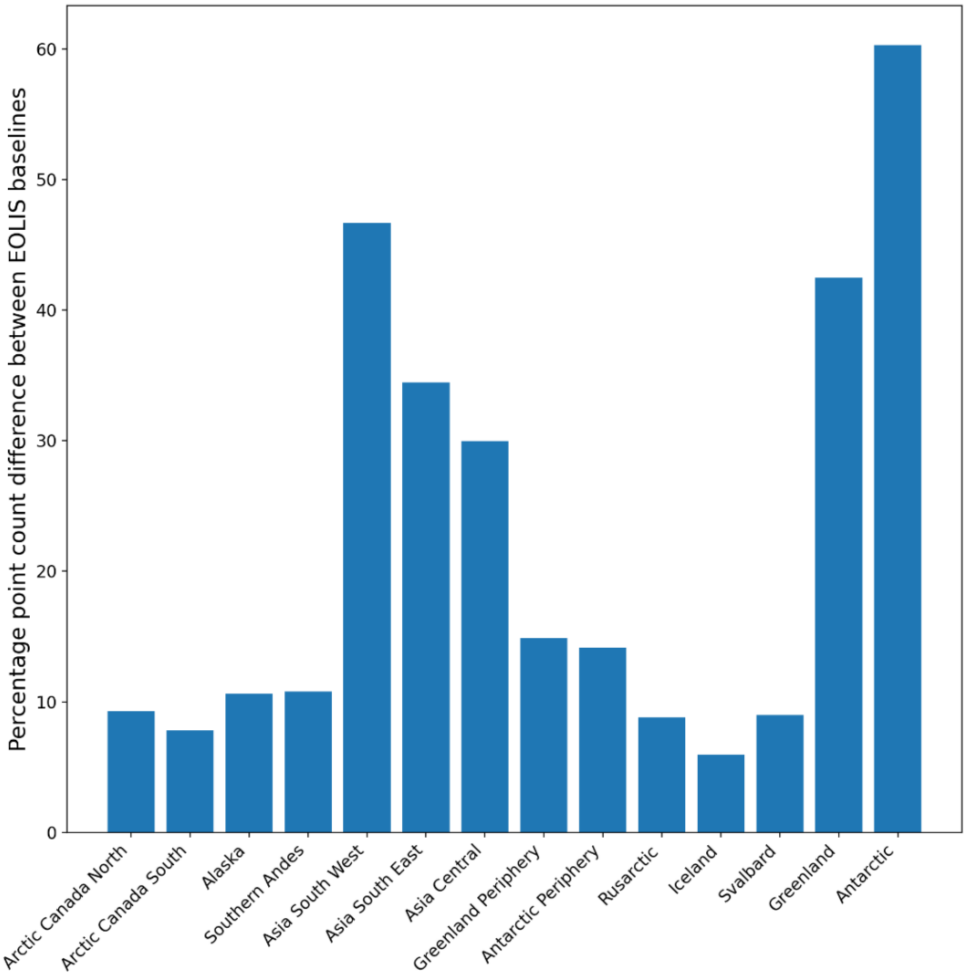

Figure 7: Percentage difference in point counts between CryoTEMPO-EOLIS baseline 2 and baseline 1 point products for December 2022, showing increase in data volume from baseline 1 to baseline 2 across all regions.

4.3 Uncertainties

4.3.1 Point Product

The CryoTEMPO-EOLIS point product uncertainties for baseline 2 have been observed to decrease across all regions compared to baseline 1. Figure 8 illustrates the reduction in uncertainty for Svalbard, with uncertainties reducing on average by approximately 1m.

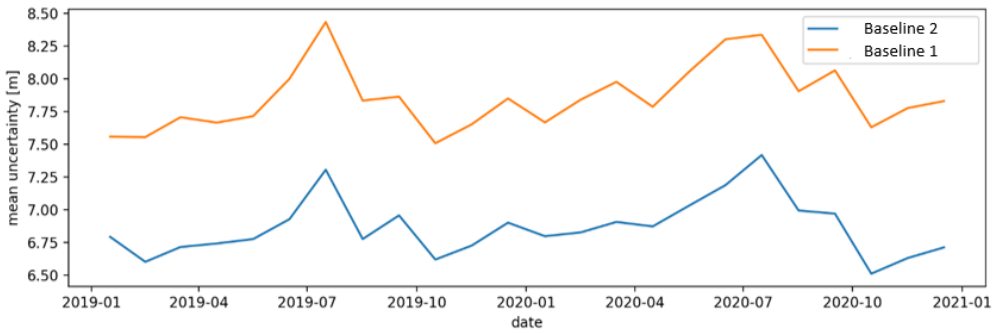

Figure 8: Mean point product uncertainty over time for Svalbard.

The uncertainty calculation for the Greenland Ice Sheet and the Antarctic Ice Sheet has been updated to use ICESat-2 ATL06 data in baseline 2, compared to OIB data in baseline 1. This has greatly increased our spatial and temporal coverage for the point uncertainty calculation. Point product uncertainties had reduced significantly with 82% of points on the Antarctic Ice Sheet having an associated uncertainty less than 5m, compared to 40% in baseline 1. A similar observation can be made for the Greenland Ice Sheet with 82% of points with uncertainty less than 5m in baseline 2, compared to 47% in baseline 1.

4.3.2 Gridded Product

Gridded uncertainties for the glacier regions have been reduced, due to the reduction in point uncertainties described above and the increase in data volume.

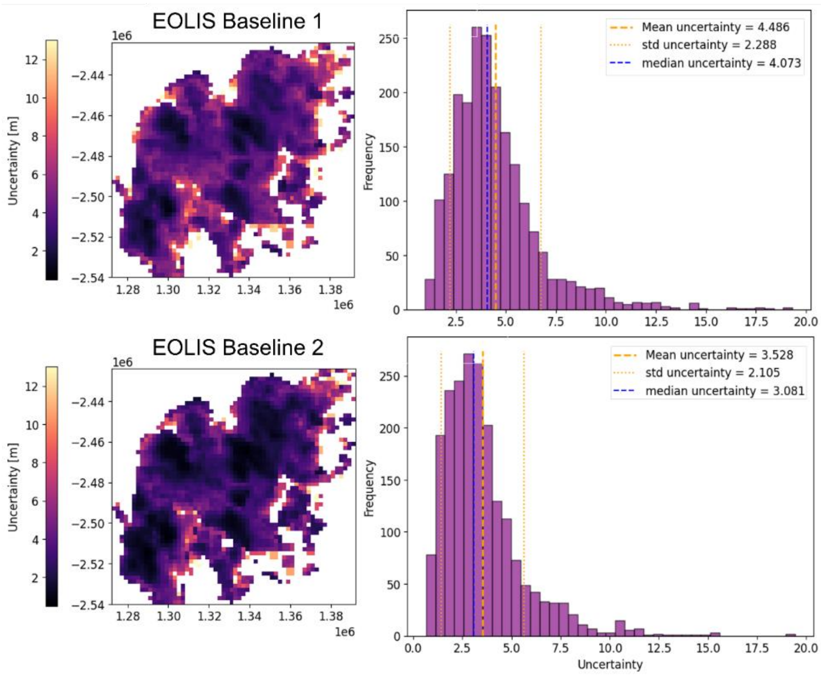

Figure 9: Reduction of uncertainties for the Vatnajökull ice cap between EOLIS Baseline 1 (top) and EOLIS Baseline 2 (bottom). The data shown is from the gridded product for February 2019. Left: uncertainty maps for the region, right: distributions of uncertainty values, with mean and median values indicated, as well as the standard deviation.

5. Capabilities and Known Limitations

5.1 Elevation Change Timeseries Derived from Gridded Products

Derived average monthly changes from CryoTEMPO-EOLIS DEMs over glaciers are shown for Austfonna, Svalbard and Vatnajökull, Iceland in Figure 11 and Figure 12, respectively. These figures illustrate that the CryoTEMPO-EOLIS gridded products are able to capture well-known events such as the surge of Basin-3, associated with rapid ice loss from mid-2012 onwards (McMillan et al., 2014; Dunse et al., 2015), and the slow-down in ice loss in Iceland between 2013 and 2015 due to recent large winter accumulation (Foresta et al., 2016). Both figures show trends comparable to other published studies using independent datasets (Wouters et al., 2019; Hugonnet et al., 2021).

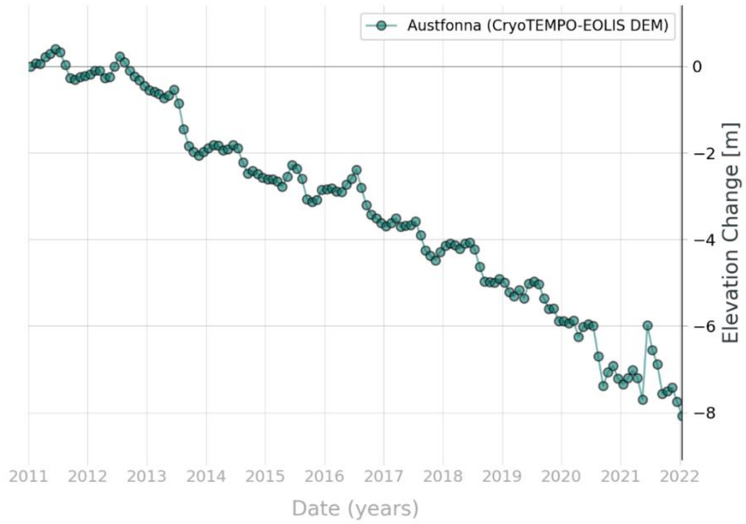

Figure 11: Cumulative monthly changes derived from the CryoTEMPO-EOLIS gridded products over Austfonna, Svalbard from 2011 to 2021.

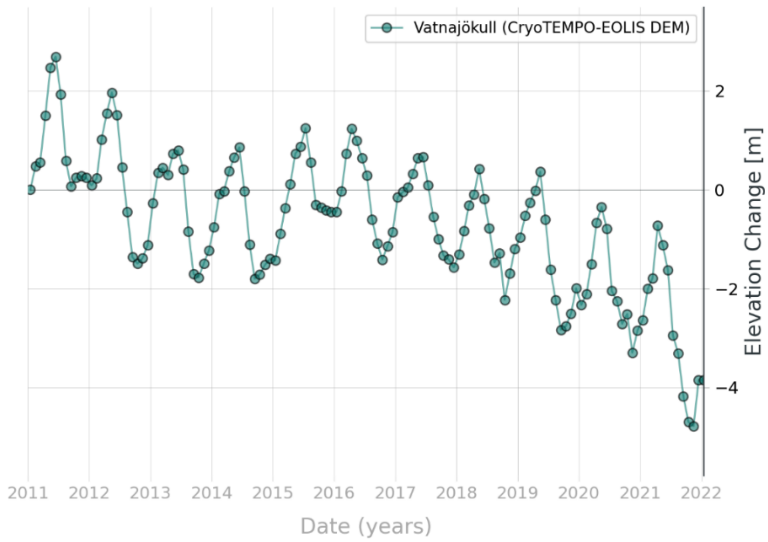

Figure 12: Cumulative monthly changes derived from the CryoTEMPO-EOLIS gridded products over Vatnajökull, Iceland from 2011 to 2021.

5.2 Spatial and Temporal Coverage of Gridded Product

Greenland and Antarctic ice sheets

Overall, gridded product coverage over the Greenland and Antarctic Ice Sheets is high at an average of 83% and 92% of total coverage respectively, where total coverage is calculated from the drainage basins masks charted in the Rignot data set (Rignot et al., 2011) minus the CryoSat-2 LRM mask. CryoSat-2 coverage in south Greenland is less extensive than further north due to latitudinal change in orbit separation, coverage can also be sparse over the Antarctic peninsula due to the complex topography. Therefore, there are some data gaps for each monthly DEM.

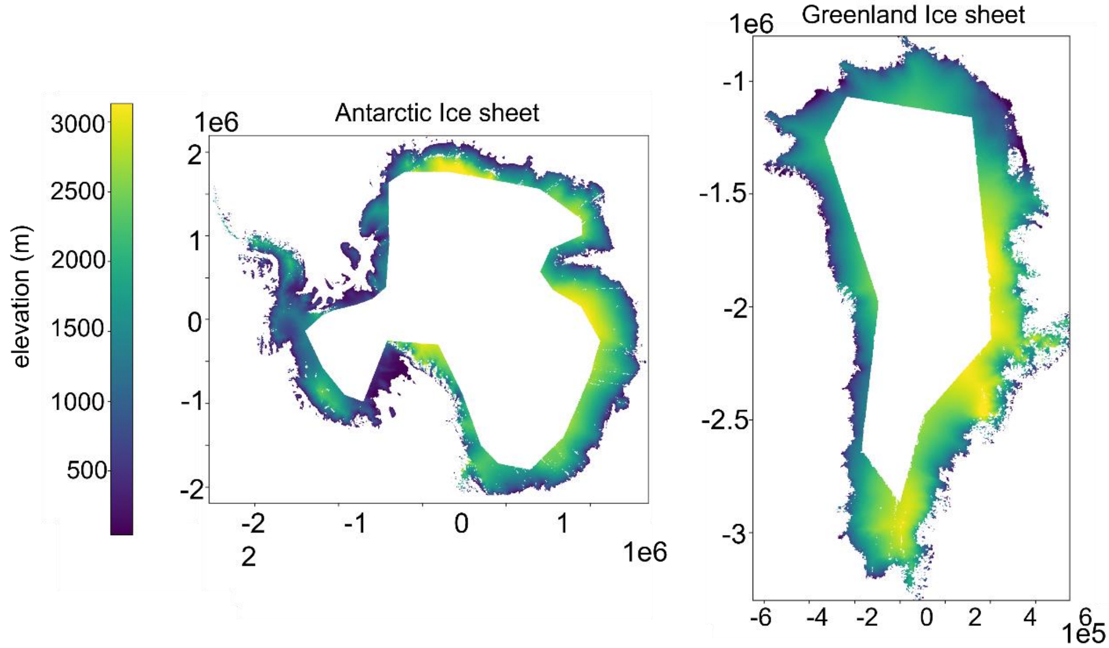

Figure 13: CryoTEMPO-EOLIS gridded products for February 2019 over the Antarctic (left) and Greenland (right) ice sheets

Ice sheet margins

Due to more complex terrain at the margins of the two ice sheets the data coverage in the CryoTEMPO-EOLIS gridded products is lower. Examples of this over the Antarctic Peninsula and East Greenland are shown in Figure 14.

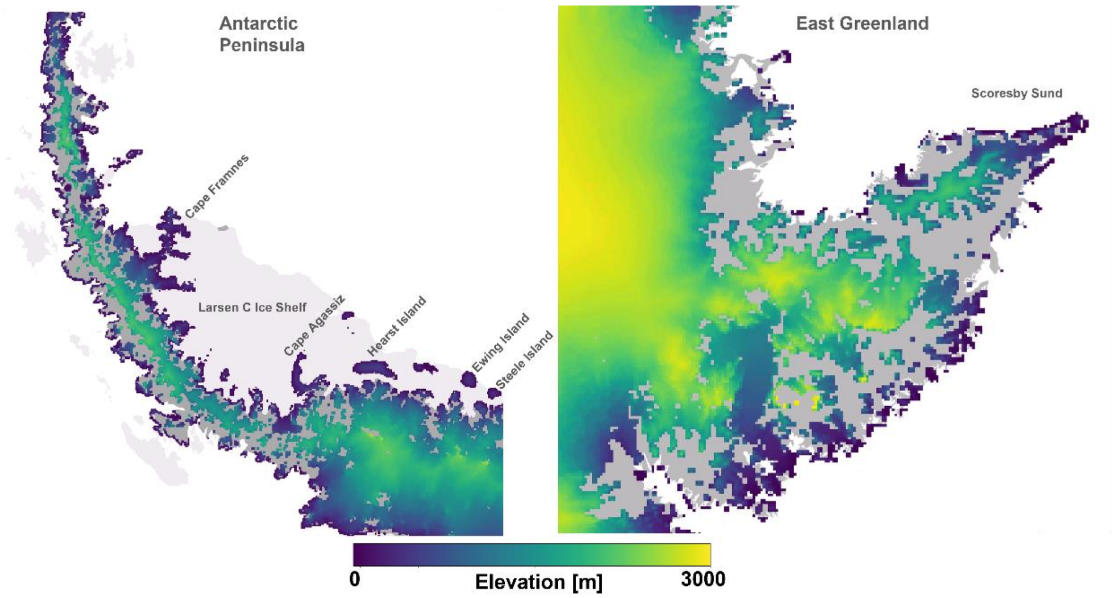

Figure 14: Coverage of the CryoTEMPO-EOLIS Gridded Product (February 2019) for two examples on the margins of the icesheets. Left: the Antarctic Peninsula, Right: an area of East Greenland south of Scoresby Sund.

Glacier Regions

Gridded product coverage in the glacier regions is variable. The region with the highest gridded coverage is Russian Arctic, with an average monthly coverage of 89%, while the lowest coverage is in Alaska, at 22.5% (both calculated at 2km resolution). Figure 15 shows a representative example from both of these regions, from May 2014. Average coverages for all regions (using data from 2010 – 2023) are detailed in Table 5 below. In each case, total coverage is calculated from the Randolph Glacier Inventory (RGI) 7.0 masks (RGI Consortium, 2017).

Table 5: Coverage information for the gridded glacier regions (averages calculated using data from 2010 – 2023)

Glacier Region	Average coverage (percentage of RGI)	Average coverage in km^2
Alaska	22.51%	40,632
Arctic Canada North	47.38%	67,096
Arctic Canada South	32.36%	24,936
Greenland periphery	57.56%	104,088
Iceland	74.09%	10,980
Svalbard	76.86%	34,832
Russian Arctic	89.16%	56,876
Southern Andes	32.59%	26,656
Antarctic Periphery	83.00%	135,944

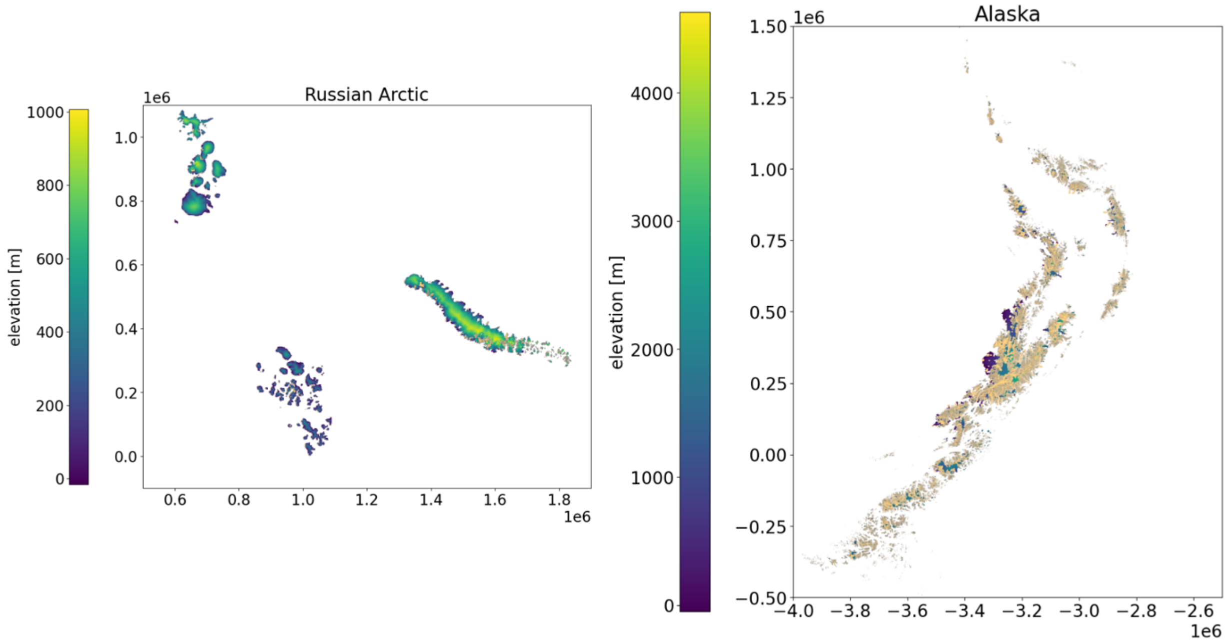

Figure 15: Example gridded coverage for Russian Arctic (left) and Alaska (right). Both examples are the gridded product from May 2014. The RGI glacier outlines are shown in orange for each region.

5.3 Phase Model Adjustment

Due to CryoSat's slight mis-pointing, the conversion from interferometric phase to angle of arrival is complex and leads to systematic errors in the angle of arrival (Wingham et al., 2004; Recchia et al., 2017). These errors are a function of surface slope, roll angle and distance from POCA. This affects predominantly areas of low surface slopes and leads to artefacts in the EOLIS elevation products. We mitigate this effect over the Ice Sheets using a simple empirical model applied on a waveform basis to the elevation difference between swath and a reference DEM, taking advantage of the systematic nature of the error. In some instances, residual phase error patterns may persist.

Due to the nature of the phase model adjustment, the shapes of some topographic features such as subglacial lakes can be altered. As shown in Figure 16, this comes from the phase model adjustment flattening out the features.

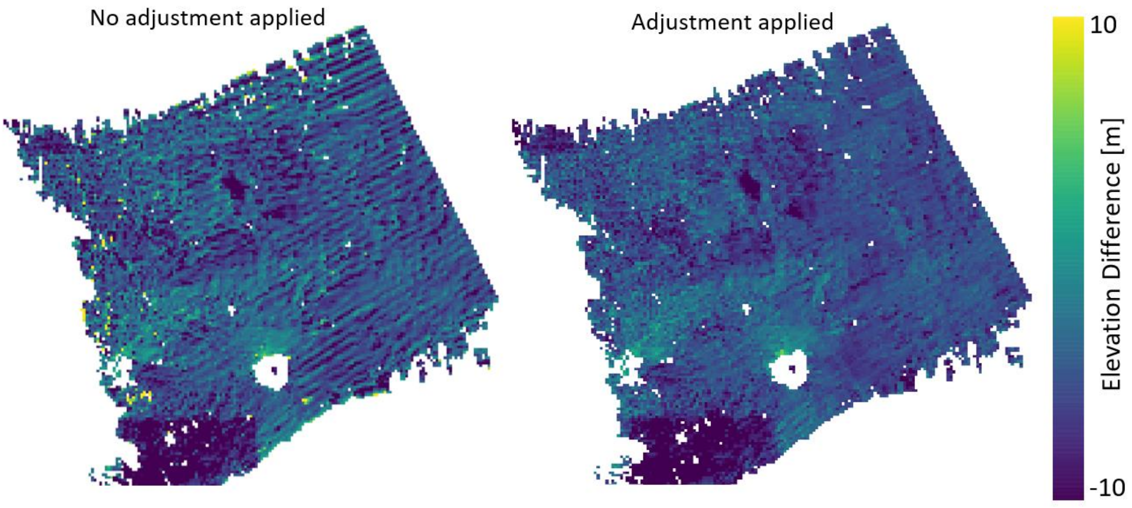

Figure 16: Elevation difference between CryoTEMPO-EOLIS DEM for February 2015 and the REMA DEM mosaic (Howat et al., 2019), over a section of Thwaites Glacier, Antarctica. The left DEM difference plot is generated with no phase model adjustment, and the right with the adjustment applied.

Figure 17 illustrates the minor subglacial lake outline deformation and blurring when the adjustment is applied compared to no adjustment. Future improvements to the products will include further development of this method.

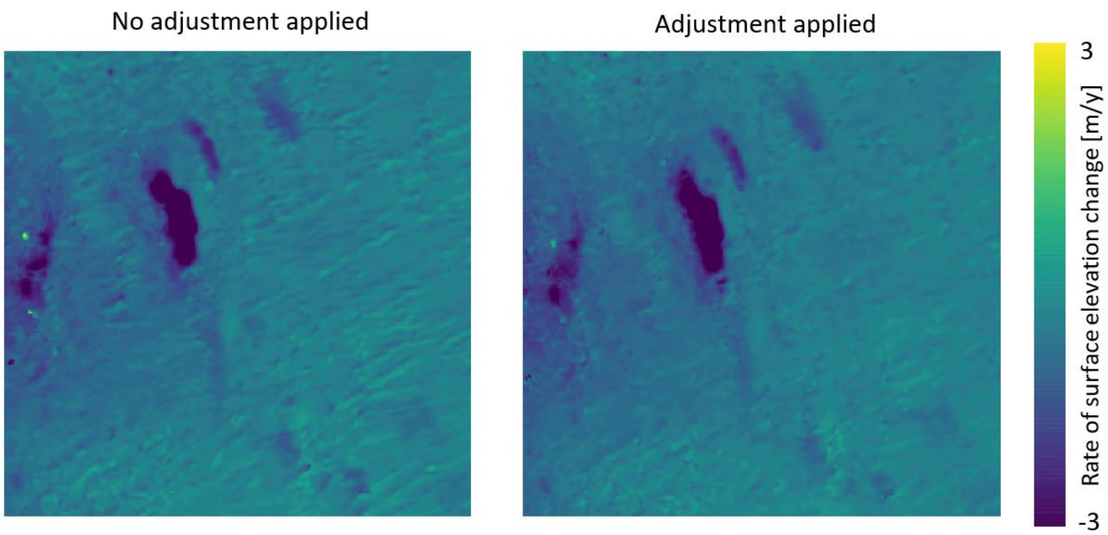

Figure 17: Rate of surface elevation change in meters per year, calculated over 5 years from January 2011 to December 2015, covering subglacial lakes located underneath Thwaites Glacier, Antarctica. The dataset with no phase model adjustment is shown on the left, and with the adjustment is presented on the right.

5.4 LRM Boundary

At the boundaries between the CryoSat-2 LRM mode and SARIn mode, we observe higher levels of noise. This results in a higher level of missing data and residual noise in the gridded product.

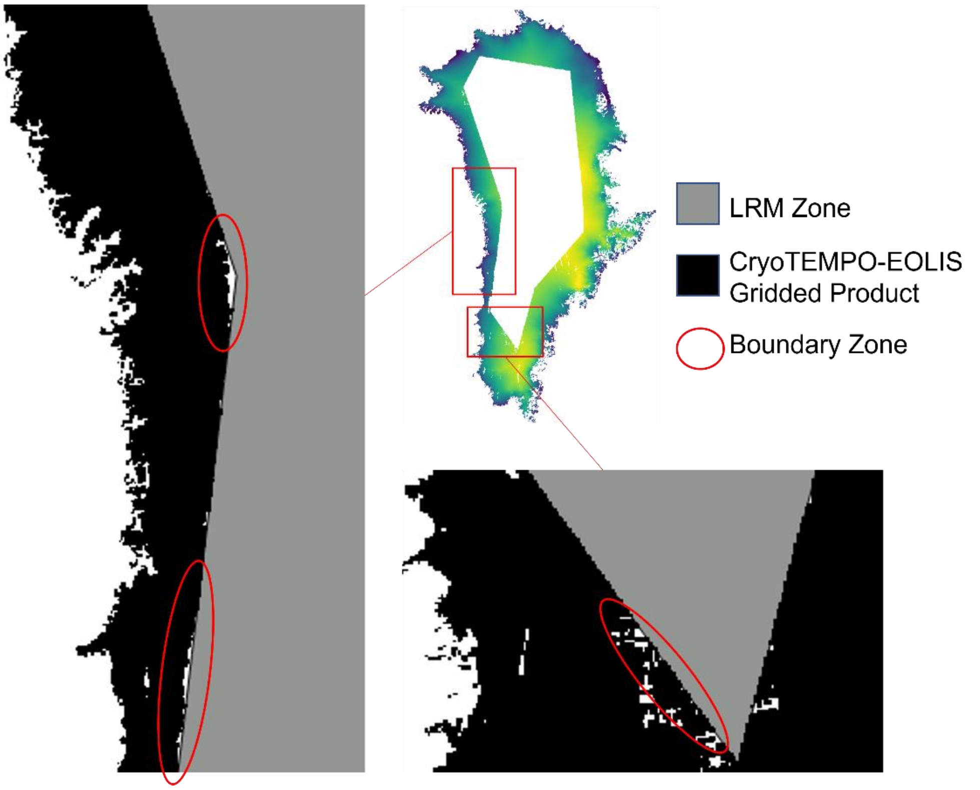

Figure 18: Example LRM boundary holes in West and South Greenland, December 2022. The red ovals highlight holes in the CryoTEMPO-EOLIS DEM next to the LRM boundary due to poor-quality data.

5.5 Single-Precision Floating-Point Errors

The EOLIS products make regular use of the float32 data type (single precision floating point). This data type is capable of accurately representing numbers that have up to 7-to-8 significant figures. The exact number of significant figures that can be represented by a float32 is dependent on the specific value of the float32.

Coordinates with 6-to-7 meaningful significant figures are occasionally encountered within EOLIS products. For example, the y-axis coordinate of southern tip of Greenland in Northern Polar Stereographic coordinates contains 7 significant figures (y=3,329,000). When this coordinate is represented as single precision float it will have an effective resolution of 0.1-1m. Lower absolute coordinate values will have better effective resolutions.

Within CryoTEMPO-EOLIS processing, whenever two or more points fall within a single float32-imposed geospatial “bin”, we select the highest coherence swath point to represent the bin, and discard all other points. In practice, this results in the loss of less than a hundredth of one percent of the points within the product.

5.6 Dataset Overlap of Ice Sheets and Peripheral Glaciers

The CryoTEMPO-EOLIS products for the Greenland Ice Sheet and the Antarctic Ice Sheet use the drainage basins masks charted in the Rignot data set (Rignot et al., 2011). For publication of the periphery glaciers of both ice sheets RGI 7.0 masks were used and as such there is cross over between both masks. Areas that are included in both the ice sheet and periphery glacier products for Greenland and Antarctica are highlighted in black in Figure 19.

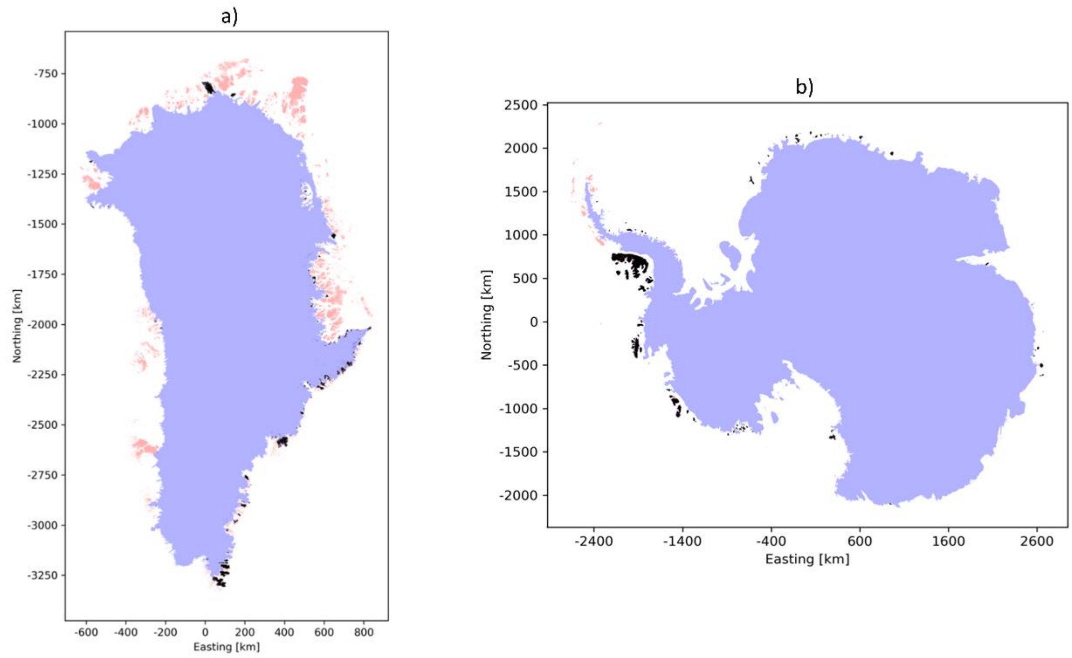

Figure 19: Map of ice sheets and glaciers over a) Greenland and b) Antarctica. Blue: area covered only by the Rignot mask, red: areas only in the RGI 7.0 mask, black: areas which are present in both masks and will be included in both products.

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Appendix

A1. Example Point Product NetCDF metadata

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Conventions: CF-1.7
Metadata_Conventions: Unidata Dataset Discovery v1.0
contact: support@cryotempo-eolis.org
creator_email: support@cryotempo-eolis.org
creator_url: http://cryotempo-eolis.org/
date_created: 2023-02-16T11:48:15.818130
date_modified: 2023-02-16T11:48:15.818142
DOI: 10.5270/CR2-2xs4q4l
title: CryoTEMPO-EOLIS Thematic Point Product
comment: CryoTEMPO-EOLIS: Elevation Over Land Ice from Swath. Point product containing elevation estimates
baseline: 2
region: alaska
summary: CryoTEMPO-EOLIS: Elevation Over Land Ice from Swath. Point product containing elevation estimates
project: CryoTEMPO-EOLIS, which is an evolution of CryoSat+ CryoTop
geospatial_y_min: 820.731191373291
geospatial_y_max: 4433.319789836094
geospatial_x_min: -3672866.90617234
geospatial_x_max: -3653905.1970112757
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geospatial_x_units: metres
geospatial_projection: +proj=stere +lat_0=90 +lat_ts=70 +lon_0=-45 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs
institution: ESA, UoE, Earthwave, isardSAT
keywords: Land Ice > Elevation Model > Elevation Points > Swath Processing > CryoSat2
keywords_vocabulary: NetCDF Climate and Forecast Standard Names
platform: Cryosat-2
processing_level: L3
version: 1
references: EOLIS elevation data generated using swath processing of CryoSat-2 data (Jakob & Gourmelen, 2023) and provided by the ESA CryoTEMPO project (https://cryotempo-eolis.org/). Jakob, L., and Gourmelen, N., (2023). Glacier Mass Loss Between 2010 and 2020 Dominated by Atmospheric Forcing. Geophysical Research Letters 50(8), 1-10. https://doi.org/10.1029/2023GL102954
source: Swath data generated from CryoSat-2 SARIn data.
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A2. Example Point Product HDR file


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     <Data_Set_Descriptor>
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      <Data_Set_Type>M</Data_Set_Type>
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      <Data_Set_Offset unit="bytes"/>
      <Data_Set_Size unit="bytes"/>
      <Num_of_Records/>
      <Record_Size/>
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```

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<Byte_Order>3210</Byte_Order>
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<Data_Set_Descriptor>
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<Data_Set_Type>M</Data_Set_Type>
<File_Name>CS_OFFL_SIR_SIN_2__20221214T133924_20221214T134307_E001.nc</File_Name>
<Data_Set_Offset unit="bytes"/>
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</Data_Set_Descriptor>
</List_of_DSDs>
</DSDs>
</SPH>
</Variable_Header>
</Earth_Explorer_Header>

A3. Example Gridded Product NetCDF metadata

```
<class 'netCDF4._netCDF4.Dataset'>
root group (NETCDF4 data model, file format HDF5):
   cdm_data_type: Gridded
   Conventions: CF-1.7
   Metadata_Conventions: Unidata Dataset Discovery v1.0
   contact: support@cryotempo-eolis.org
   creator_email: support@cryotempo-eolis.org
   creator_url: http://cryotempo-eolis.org/
   date_created: 2023-02-24T01:03:41.921442
   date_modified: 2023-02-24T01:03:41.921473
   DOI: 10.5270/CR2-2xs4q4l
   title: CryoTEMPO-EOLIS Thematic Gridded Product
   comment: CryoTEMPO-EOLIS: Elevation Over Land Ice from Swath. Gridded product containing elevation estimates on a regular grid
   region: antarctic
   baseline: 2
   summary: CryoTEMPO-EOLIS: Elevation Over Land Ice from Swath. Gridded product containing elevation estimates on a regular grid
   version: 1
   geospatial_y_min: -2200000
   geospatial_y_max: 2200000
   geospatial_x_min: -2600000
   geospatial_x_max: 2700000
   geospatial_y_units: metres
   geospatial_x_units: metres
   geospatial_projection: '+proj=stere +lat_0=-90 +lat_ts=-71 +lon_0=0 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs'
   geospatial_resolution: 2000
   geospatial_resolution_units: metres
   institution: ESA, UoE, Earthwave, isardSAT
   keywords: Land Ice > Gridded > Elevation Model  > Elevation Points > Swath Processing > CryoSat-2
   keywords_vocabulary: NetCDF Climate and Forecast Standard Names
   platform:  Cryosat-2
   processing_level: L3
   project: CryoTEMPO-EOLIS, which is an evolution of CryoSat+ CryoTop
   references: EOLIS elevation data generated using swath processing of CryoSat-2 data (Gourmelen et al., 2018) and provided by the ESA CryoTEMPO project (https://cryotempo-eolis.org/). Gourmelen, N., Escorihuela, M., Shepherd, A., Foresta, L., Muir, A., Garcia-Mondejar, A., Roca, M., Baker, S., & Drinkwater, M. R. (2018). CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change. Advances in Space Research, 62(6), 1226-1242. https://doi.org/10.1016/j.asr.2017.11.014
   time_coverage_duration: P3M
   time_coverage_start: 2019-01-01T00:00:00+00:00
   time_coverage_end: 2019-03-31T23:59:59+00:00
   dimensions(sizes): x(2650), y(2200), time(1), nv(2)
   variables(dimensions): int32 time(time), float32 x(x), float32 y(y), float32 elevation(x, y, time), float32 uncertainty(x, y, time), int32 nv(nv), float32 x_bnds(x, nv), float32 y_bnds(y, nv)
```

A4. Example Gridded Product HDR file


```
<Earth_Explorer_Header>
 <Fixed_Header>
  <File_Name>CS_OFFL_THEM_GRID__ANTARCTIC_2019_02_V201</File_Name>
  <File_Description>L3 Gridded thematic product containing interpolated swath data that is generated from CryoSat2
SARIN data.</File_Description>
  <Notes/>
  <Mission>CryoSat</Mission>
  <File_Type>THEM_GRID_</File_Type>
  <Validity_Period>
   <Validity_Start>UTC=2019-01-01T00:00:00+00:00</Validity_Start>
   <Validity_Stop>UTC=2019-03-31T23:59:59+00:00</Validity_Stop>
  </Validity_Period>
  <File_Version>0001</File_Version>
  <Source>
   <System>Tempo IPF</System>
   <Creator>Earthwave</Creator>
   <Creator_Version>0.1</Creator_Version>
   <Creation_Date>UTC=2023-02-24T01:03:42.000937</Creation_Date>
  </Source>
  <File_Class>Off-Line Processing</File_Class>
 </Fixed_Header>
 <Variable_Header>
  <MPH>
   <Product>CS_OFFL_THEM_GRID__ANTARCTIC_2019_02_V001</Product>
   <Proc_Stage_Code>OFFL</Proc_Stage_Code>
   <Ref_Doc>http://www.cryotempo-eolis.org</Ref_Doc>
   <Software_Version>Earthwave/1.3.1</Software_Version>
   <Proc_Time>UTC=2023-02-24T01:03:42.068448</Proc_Time>
   <Tot_size unit="bytes">46716314</Tot_size>
  </MPH>
  <SPH>
   <Product_Location>
    <Min_X proj4="'+proj=stere +lat_0=-90 +lat_ts=-71 +lon_0=0 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m
+no_defs'" unit="metres">-2600000</Min_X>
    <Max_X proj4="'+proj=stere +lat_0=-90 +lat_ts=-71 +lon_0=0 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m
+no_defs'" unit="metres">2700000</Max_X>
    <Min_Y proj4="'+proj=stere +lat_0=-90 +lat_ts=-71 +lon_0=0 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m
+no_defs'" unit="metres">-2200000</Min_Y>
    <Max_Y proj4="'+proj=stere +lat_0=-90 +lat_ts=-71 +lon_0=0 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m
+no_defs'" unit="metres">2200000</Max_Y>
   </Product_Location>
   <Resolution>
    <Grid_Pixel_Width units="metres">2000</Grid_Pixel_Width>
    <Grid_Pixel_Height units="metres">2000</Grid_Pixel_Height>
   </Resolution>
   <Interpolation_Window>
    <Window_Start>UTC=2019-01-01T00:00:00+00:00</Window_Start>
    <Window_End>UTC=2019-03-31T23:59:59+00:00</Window_End>
    <Window_Centre>UTC=2019-02-15T00:00:00+00:00</Window_Centre>
   </Interpolation_Window>
   <DSDs>
    <List_of_DSDs count="0"/>
   </DSDs>
  </SPH>
 </Variable_Header>
</Earth_Explorer_Header>
```