

Cryo-TEMPO

Algorithm Theoretical Basis Document

Winter Sea Ice



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Change Log

Issue	Author	Affected Section	Change	Status
0	Stefan Hendricks, AWI	All	Document Creation	Complete
1.1	Stefan Hendricks, AWI	All	Version 1 Content	Complete
1.2	Stefan Hendricks, AWI	All	Version 1 Revisions	Complete
2.1	Stefan Hendricks, AWI	All	Algorithm Update (Phase 2.1)	Complete
3.1	Stefan Hendricks, AWI	All	Algorithm Update (Phase 2.2)	Complete
3.2	Stefan Hendricks, AWI	All	Version 3 Revisions	Complete
4.1	Stefan Hendricks, AWI	4.3.3.1 SAMOSA+ retracker 4.3.7 Filtering 4.4 Gridded Data	Algorithm Update (Phase 3.1)	Complete
4.2	Stefan Hendricks, AWI	2.0 Baseline Change Log 5.3.3.2 Threshold First Maximum Retracker Algorithm (TFMRA) 5.3.4 Surface Elevations and Range Corrections 5.3.7 Filtering	Version 4.1 revisions	Under Review

Acronyms and Abbreviations

AD	Applicable Document	REAPER	REprocessing of Altimeter Products for ERs
ADT	Absolute Dynamic Topography	RFW	Request for Waiver
ATM	Airborne Topographic Mapper	RMSD	Root mean square difference
AWI	Alfred Wegener Institute	SAR	Synthetic Aperture Radar
C3S	Copernicus Climate Change Service	SARIn	Synthetic Aperture Radar Interferometric
CCI	Climate Change Initiative	SL	Science Lead
CCN	Contract Change Notice	SLA	Sea Level Anomaly
CLS	Collecte Localisation Satellites	SIGMAo	Sigma Nought
CNES	Centre National des Etudes Spatiales (French Space Agency)	SoW	Statement of Work
CNR	Consiglio Nazionale delle Ricerche	SS	Shepherd Space
CPOM	Centre for Polar Observation & Modelling	TCOG	Threshold Centre of Gravity
CR	Change Request	TDP	Thematic Data Product
CRISTAL	Copernicus Polar Ice and Snow Topography Altimeter	TFMRA	Threshold First Maximum Retracker Algorithm
CryoVEx	Cryosat Validation Experiment (field campaigns)	TUG	Thematic User Group
DAHITI	Database for Hydrological Time Series of Inland Waters	UCL	University College London
DEM	Digital Elevation Model	UCM	User Consultation Meeting
DTU	Technical University of Denmark	WP	Work Package
EO	Earth Observation		
ERR	Evolutions Recommendation Report		
ESA	European Space Agency		
FIS	Finnish Ice Service		
FMI	Finnish Meteorological Institute		
FRAPPE	Flexible Radar Altimeter Processor for Performance Evaluation		
FRM4ALT	Fiducial Reference Measurement for Altimetry		
FRD4ALT	Fundamental Data Records for Altimetry		
FYI	First-year sea ice		
G-REALM	Global Reservoirs and Lakes Monitor		
IMEDEA	Instituto Mediterráneo de Estudios Avanzados		
IPCC	Intergovernmental Panel on Climate Change		
IRPI	Istituto di Ricerca per la Protezione Idrogeologica		
ISRO	Indian Space Research Organisation		
ITT	Invitation To Tender		
JPL	Jet Propulsion Laboratory		
LEGOS	Laboratoire d'Étude en Géophysique et Océanographie Spatiale		
LEW	Leading Edge Width		
LRM	Low Resolution Mode		
LU	Lancaster University		
MDT	Mean Dynamic Topography		
MSS	Mean Sea Surface		
MSSL	Mullard Space Science Laboratory (part of UCL)		
MYI	Multi-year sea ice		
NCR	Non Conformance Report		
NERSC	Nansen Environmental and Remote Sensing Center		
NSIDC	National Snow and Ice Data Center		
OCOG	Offset Centre Of Gravity retracker		
PDS	Payload Data Segment		
PEG	Polar Expert Group		
PM	Project Manager		
PO	Polar Oceans		
PP	Pulse Peakiness		
PSMSL	Permanent Service for Mean Sea Level		
RA	Radar Altimeter / Altimetry		

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1 INTRODUCTION

1.1 Purpose and Scope

This document comprises the Algorithm Theoretical Basis (ATBD) for the Winter Sea Ice algorithms used for the *CryoSat-2 ThEMatic PrOducts (Cryo-TEMPO)* study, Ref: ESA AO/1-10244/2-/I-NS. The ATBD has been written by the sea ice team led by the Alfred Wegener Institute, with contributions from all members of the Cryo-TEMPO consortium. Lancaster University as the prime contractor is the contact point for all communications regarding this document.

The Algorithm Theoretical Basis Document (ATBD) provides a high-level description of the algorithms and processing used to produce each Cryo-TEMPO Winter Sea Ice product parameter.

1.2 Document Structure

This document describes the algorithms of the sea ice processing chain. The document is structured as follows:

- Section 1 – Introduction
- Section 2 – Sea Ice Parameters
- Section 3 – Overall Sea Ice Processing Flow
- Section 4 – Algorithm Descriptions
- Section 5 – Data Examples
- Section 6 – Known Issues

1.3 Applicable and Reference Documents

Applicable documents

Reference	Title
AD1	Statement of Work ESA Express Procurement Plus - EXPRO+ CryoSat-2 ThEMatic PrOducts Cryo-TEMPO, Issue 1, Revision 0, Date of Issue 01/04/2020 [Ref. ESA-EOPG-EOPGMQ-SOW-10].
AD2	Invitation to Tender for CryoSat-2 ThEMatic PrOducts Cryo-TEMPO REF.: ESA AO/1-10244/2-/I-NS [Ref. SA-IPL-POE-NS-sp-LE-2020-313].
AD3	Draft Contract, CryoSat-2 ThEMatic PrOducts Cryo-TEMPO, Appendix 2 to ESA AO/1-10244/20/I-NS.

Reference documents

Reference	Title
RD1	Copernicus Polar and Snow Cover Applications User Requirements Workshop, http://www.copernicus.eu/polar-snow-workshop
RD2	PEG-1 Report, User Requirements for a Copernicus Polar Mission, Step 1 Report, Polar Expert Group, Issue: 12th June 2017
RD3	PEG-2 Report, Polar Expert Group, Phase 2 Report on Users Requirements, Issue: 31st July 2017

2 BASELINE CHANGE LOG

This section details the main changes between each Cryo-TEMPO Winter Sea Ice processing baseline. A processing baseline is the fixed state of the algorithms, auxiliary data, configuration files and processing software used to process the full mission from ESA L1b files through to Cryo-TEMPO sea ice products.

2.1 Baseline-A

Baseline-A was the first Cryo-TEMPO Winter Sea Ice product, released in January 2022.

2.2 Baseline-B

Released in Q1 2023. This section describes the changes implemented in Baseline-B as compared to the previous baseline.

Algorithm	Description of change
New Variable / Mask	Added a region code flag for each data record. The region codes are based on the 2021 NSIDC regional mask for Arctic sea ice trends and climatologies (credit J. Scott Stewart and Walter N. Meier, NSIDC).
Land/ocean mask	Updated a new land/ocean mask to improve data coverage around Greenland and in the Canadian Archipelago. Before, the land mask included in CryoSat-2 L1b files was used.
Geophysical Corrections	Updated tide model to the Regional Arctic Tide Model v1.1 (Cancet et al, 2022) blended with FES2014. Before the tidal solutions included in CryoSat-2 L1b files were used.
Geophysical Corrections	Used dynamic atmosphere correction instead of the inverse barometric correction. This improves sea level anomaly computations on the Arctic Shelves (Doglioni et al., 2023).
Mean Sea Surface	Update mean sea surface from DTU15 to DTU21.

2.3 Baseline-C

Released in Q2 2024. This section describes the changes implemented in Baseline-C as compared to the previous baseline.

Algorithm	Description of change
New Product	Extend data coverage to southern hemisphere.
New Product	Deliver the thematic winter sea ice product in near-real time.
Retracker	Replaced TFMRA retracker with SAMOSA+ for sea ice and lead waveforms (this change does not apply to the near real-time product).
Surface Type Classification	Update the surface type classification (unknown, ocean, lead & sea ice) to the most recent version used in the ESA Climate Change Initiative – Sea Ice Project.

2.4 Baseline-D

To be released in Q1 2025. This section describes the changes implemented in Baseline-D as compared to the previous baseline.

Algorithm	Description of change
New product	Added gridded Level-3 data for the northern and southern hemisphere.
Geophysical Corrections	Update tidal model to FES2022.
Retracker	Added sub-waveform retracking of sea ice waveforms using SAMOSA+. This change has been implemented to improve the accuracy of SAMOSA+ for waveforms from heterogenous sea ice conditions.
Uncertainty	Compute range uncertainty directly from the SAMOSA+ fitting process. Before, the range uncertainty was a fixed value (expert guess).
Filter	Use SAMOSA+ retracker properties to filter radar freeboard data when the main waveform peak is likely from an off-nadir target.
New Variable / Filter	Added marginal ice zone filter flag. The filter flags freeboard values that are likely biased by ocean swell in the marginal ice zone.

3 SEA ICE PARAMETER

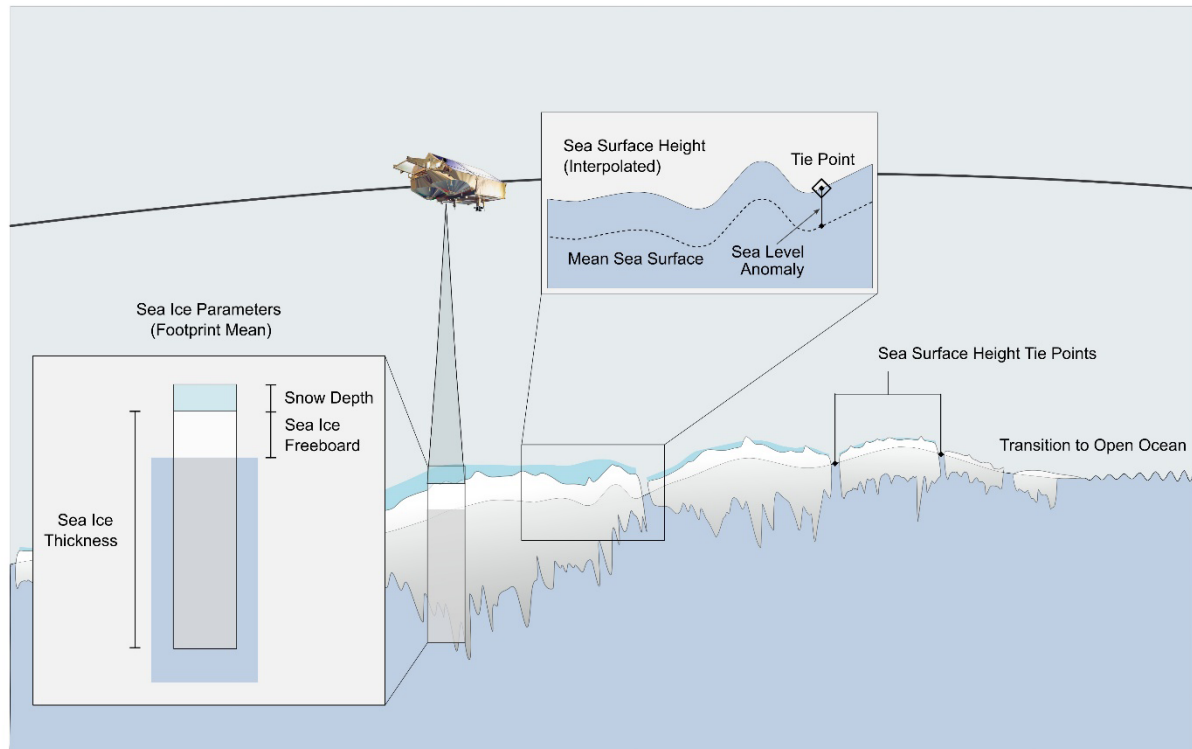


Figure 1: Schematic of sea-ice freeboard and snow depth retrieval from CryoSat-2 altimeter track data

3.1 Parameter Definition

The Cryo-TEMPO thematic Winter Sea Ice product contains geolocated and time-associated sea-ice freeboard, the elevation of the ice surface above local sea level as well as snow depth on sea ice. Both variables are fundamental input parameters for the estimation of sea-ice thickness. Sea ice thickness and snow depth have also recently been acknowledged as Essential Climate Variables (ECV) (Lavergne et al., 2022). A full definition of the two parameters as well as their standardized names are given in Table 1.

The product files contain information at the full resolution of CryoSat's radar altimeter SIRAL since the geophysical retrieval is based on input data of individual orbits in the polar regions. The geophysical output maintains the location and time of each radar waveform in the CryoSat-2 Level-1b sensor data along the trajectory and thus fulfils the requirements for level 2 data processing.

Sea ice freeboard is the geophysical parameter that is directly derived from observations by the radar altimeter, except for a range correction over ice surfaces that depends on external snow depth information. Freeboard is expected to show variability at scales significantly smaller than the size of the CryoSat-2 footprint, thus the presented values in the product files indicate the mean sea-ice

freeboard within the CryoSat-2 footprint. Significant variability between adjacent observations is also expected due to true variability as well as sensor noise and potential retrieval biases.

Snow depth on sea ice instead is not measured by the CryoSat-2 radar altimeter and the information in the Cryo-TEMPO thematic sea ice product originate from lower resolution auxiliary data sources. Snow depth data is nevertheless provided at full spatial resolution as it is an input parameter for the per-waveform sea-ice freeboard retrieval. Like sea-ice freeboard, the snow depth values are expected to represent the mean snow depth in the CryoSat-2 footprint.

Table 1: Definition of geophysical sea ice variables and their names in the Cryo-TEMPO thematic winter sea ice product. Standard names and the definition are taken and modified from the table of standard names for the Climate and Forecast (CF) metadata conventions for earth science datasets.

Parameter	Property	
Sea Ice Freeboard	<i>Variable Name</i>	sea_ice_freeboard
	<i>Unit</i>	meter (m)
	<i>CF Standard Name</i>	sea_ice_freeboard
	<i>Definition</i>	Sea ice freeboard is the mean height of the sea-ice surface above the water surface in the horizontal domain. "Sea ice" means all ice floating in the sea which has formed from freezing sea water, rather than by other processes such as calving of land ice to form icebergs.
Sea Ice Freeboard Uncertainty	<i>Variable Name</i>	sea_ice_freeboard_uncertainty
	<i>Unit</i>	meter (m)
	<i>CF Standard Name</i>	sea_ice_freeboard_standard_error
	<i>Definition</i>	The retrieval uncertainty of sea-ice freeboard
Filtered Sea Ice Freeboard	<i>Variable Name</i>	sea_ice_freeboard_filtered
	<i>Unit</i>	meter (m)
	<i>CF Standard Name</i>	sea_ice_freeboard
	<i>Definition</i>	A smoothed representation of sea_ice_freeboard with an along-track lowess filter.
Radar Freeboard	<i>Variable Name</i>	radar_freeboard
	<i>Unit</i>	meter (m)
	<i>CF Standard Name</i>	-
	<i>Definition</i>	Freeboard measurement of the radar altimeter. Does not contain a range offset correcting for a signal delay caused by the radar wave propagation through the snow layer.
Radar Freeboard Uncertainty	<i>Variable Name</i>	radar_freeboard_uncertainty
	<i>Unit</i>	meter (m)
	<i>CF Standard Name</i>	-
	<i>Definition</i>	The retrieval uncertainty of radar freeboard
Snow Depth on Sea Ice	<i>Variable Name</i>	snow_depth
	<i>Unit</i>	meter (m)
	<i>CF Standard Name</i>	surface_snow_thickness
	<i>Definition</i>	Surface snow refers to the snow on the solid ground or on surface ice cover, but excludes, for example, falling snowflakes. "Thickness" means the vertical extent of a layer and is assumed to apply to the whole area of each horizontal domain.
Snow Depth Uncertainty	<i>Variable Name</i>	snow_depth_uncertainty
	<i>Unit</i>	meter (m)
	<i>CF Standard Name</i>	surface_snow_thickness_standard_error
	<i>Definition</i>	The uncertainty of snow depth on sea ice from the source climatologies

Table 2: Definition of geolocation variables and their names in the Cryo-TEMPO thematic winter sea ice product. Standard names and the definition are taken and modified from the table of standard names for the Climate and Forecast (CF) metadata conventions for earth science datasets.

Parameter	Property	
time	<i>Variable Name</i>	time
	<i>Unit</i>	seconds since 2000-01-01 00:00:00
	<i>CF Standard Name</i>	time
	<i>Definition</i>	UTC time counted in seconds since 2000-01-01 00:00:00 (Gregorian calendar)
Longitude	<i>Variable Name</i>	longitude
	<i>Unit</i>	degrees east
	<i>CF Standard Name</i>	longitude
	<i>Definition</i>	Longitude of satellite nadir measurement location [-180, 180]. Positive longitude is East relative to Greenwich meridian.
Latitude	<i>Variable Name</i>	latitude
	<i>Unit</i>	Degrees north
	<i>CF Standard Name</i>	latitude
	<i>Definition</i>	Latitude of satellite nadir measurement location [-90, +90]. Positive latitude is North latitude, negative latitude is South latitude.

3.2 Target Audience and Intended Use

The target audience for Cryo-TEMPO thematic winter sea ice product are users of sea ice remote sensing data who require access for low level geophysical parameters with the full resolution and a minimum of applied processing steps and assumptions made therein.

Potential use cases are for example:

1. Evaluation of custom sea-ice freeboard algorithms
2. Implementation of custom sea-ice freeboard to sea-ice thickness conversion processing chains.
3. Using sea-ice freeboard data for customized grids or aggregated time periods
4. Using sea-ice freeboard as an analogue to an observation operator as low-level comparison between satellite remote sensing and numerical sea-ice simulations.

While sea-ice thickness is a required parameter for many end-users in climate research and operational sea-ice remote sensing applications, it is not included in the Cryo-TEMPO thematic sea ice product due to the scope of a low-level sea-ice remote sensing data set. However, user feedback is welcome, and the content of the thematic sea ice product may be extended in future versions.

3.3 Geographical Coverage

The Cryo-TEMPO thematic winter sea ice product covers both hemispheres. The northern hemisphere is defined as all CryoSat-2 SAR and SARin data over sea-ice covered regions north of 45N (see Figure 2), while the southern hemisphere data contains all SAR and SARin data south of 45S.

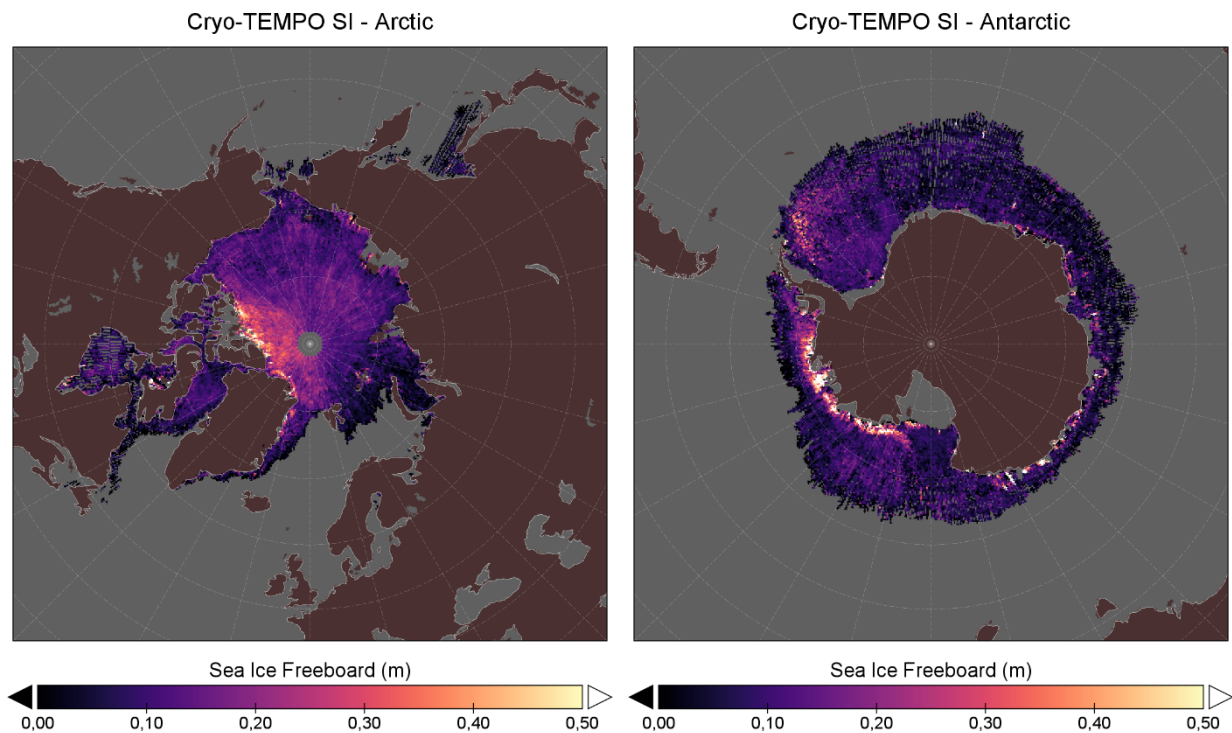


Figure 2: Geographical coverage of the Cryo-TEMPO thematic winter sea ice product in the northern (left) and southern hemisphere (right) Both panels contain 1 month of data.

4 OVERALL WINTER SEA ICE PROCESSING FLOW

The fundamental principle of sea-ice freeboard retrieval is based on measuring the elevations of sea ice surfaces and the local sea level at fractures in the ice cover. Sea ice freeboard is then computed by taking the difference between the sea ice elevations, corrected to account for propagation through the snow layer, and an interpolated sea level along the satellite track (see Figure 1). The processing is applied to each polar orbit individually.

This geophysical processing chain is broken down into several distinct sub-steps (

Figure 3):

1. Surface type classification of each waveform into categories of open ocean, lead (water or very thin ice at fractures of the sea ice covers, sea ice and ambiguous. (See Section 5.3.2).
2. Estimation of radar range (retracking) between the satellite and the surface for each waveform of the surface types lead and sea ice.
3. Computation of surface elevation by subtracting radar range from the altitude of the satellite.
4. Application of range corrections to the elevation profile to account for signal delay effects caused by varying radar wave propagation speed in the iono- and troposphere.
5. Removal of the effect of tides on the along-track elevations
6. Removal of static sea surface height variations by subtracting a mean sea surface height from the along-track elevations.
7. Along-track interpolation of the sea-level anomaly from the discrete observations (lead elevations) of sea surface height in the ice cover.
8. Range correction over snow covered sea ice due to the lower wave propagation speed inside the snow layer.

The estimation of the along-track sea-level anomaly is shared with the polar ocean thematic product and implemented in a consistent way. There are two main assumptions in the processing:

1. All parameter values represent the mean value in the radar altimeter footprint.
2. The retracker range estimate for Ku-Band altimeter data in the Arctic winter season corresponds to the mean of the snow/ice interface elevation distribution.

The limitations of these assumptions are discussed in section 6.

The overall processing flow depends on the primary radar altimeter data as well as several auxiliary data sets that are required for accurate retrieval of sea-surface height and sea-ice freeboard:

1. Sea Ice Concentration data is used as a daily sea-ice mask aiding the surface type classification.

2. A static mean sea surface describes the average variation of the ocean surface. Removing this variation from the along-track elevations reduces the probability of interpolation errors between distant instantaneous sea-surface height observations at the location of leads.
3. A Snow climatology describes the average monthly evolution of snow depth on sea ice. Snow depth and density information is required to apply a range correction caused by the specific radar wave propagation speed in the snow layer in sea-ice freeboard retrieval process.
4. Sea ice type data is used as input to the estimation of snow depth in the central Arctic Basin. This step is required because the snow depth climatology must be applied with separate value for first-year (FYI) and multi-year (MYI) sea ice and the region and temporal distribution of the two sea ice classifications is provided by an external daily gridded sea-ice type data set.

The specifications of the primary and auxiliary data sets are described in 5.1.

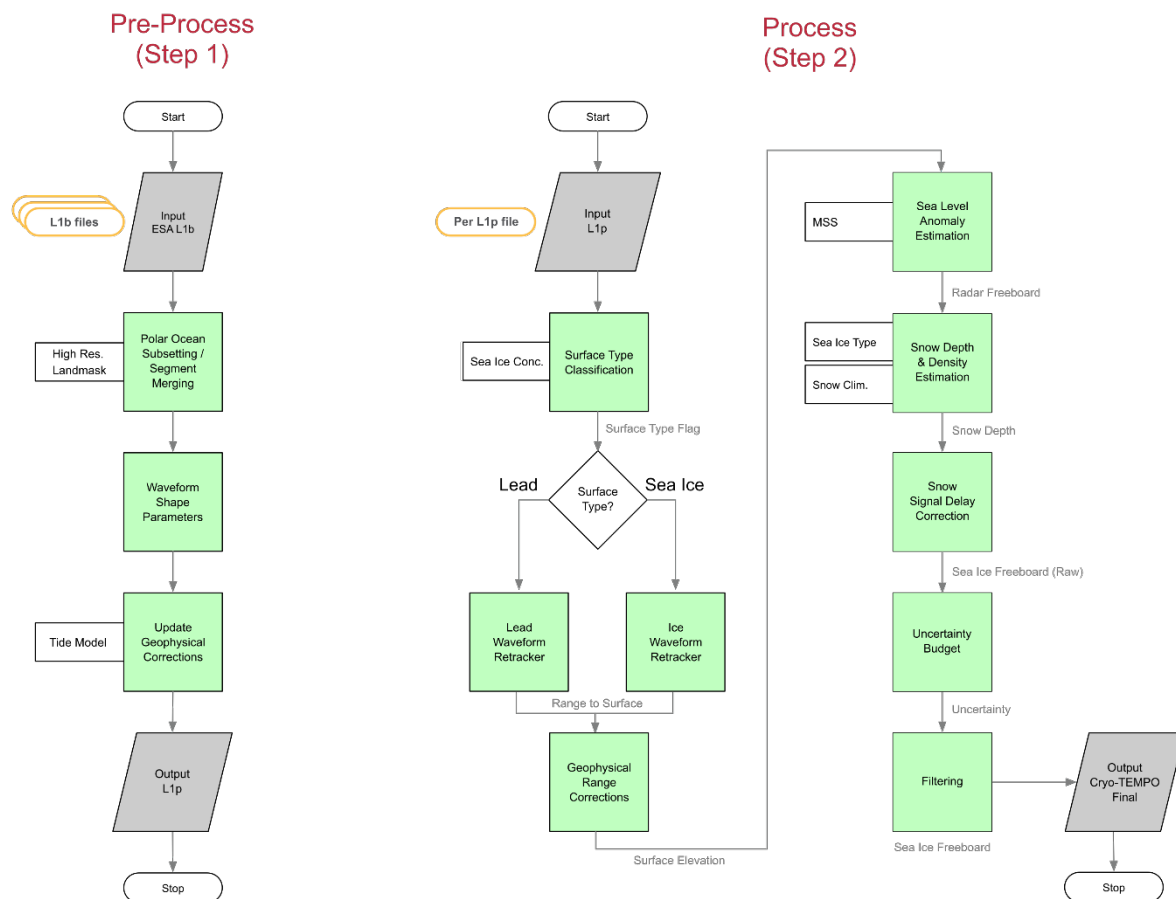


Figure 3: Processing workflow of geophysical retrieval of sea-ice freeboard and snow depth on sea ice for the Cryo-TEMPO winter sea ice product.

4.1 Differences between near real-time and offline products

The near real-time (NRT) and offline (non time critical; NTC) products differ in the available input data and algorithm choices. Specifically, the near real-time freeboards are based on the faster TFMRA retracker, while the offline products use SAMOSA+ retracker. A full list of differences is given in Table 3.

Table 3: Data source and algorithm differences between near real-time and offline products

	Near real-time (NRT) product	Offline (NTC) product	Section (this document)
CryoSat-2 input data	NRT	Offline	5.1.1
Sea Ice Concentration	OSI-SAF NRT	OSI-SAF climate data records	5.1.2.1
Sea Ice Type	OSI-SAF NRT	OSI-SAF climate data records	5.1.2.2
Retracker	TFMRA	SAMOSA+	5.3.3
Radar Freeboard Filter	-	Based on SAMOSA+ misfit	5.3.7.1
Marginal Ice Zone Filter	Based on waveform shape properties	Based on SAMOSA+ significant waveheight	5.3.7.3

5 ALGORITHM DESCRIPTION

5.1 Source Data

Input data to the sea ice processing algorithm falls into two categories:

1. Primary data: Radar altimeter data from the CryoSat's SIRAL.
2. Auxiliary data: External data sets aiding the calibration or geophysical retrieval.

Each data set is described in corresponding sections below.

5.1.1 CryoSat-2 altimeter data

Primary input data to the Cryo-TEMPO thematic sea ice product is Level-1b data from the ESA CryoSat-2 baseline-E ICE processing chain for SAR and SARin radar modes. The files are delivered as one netCDF file separated by changes of the radar mode in near real-time and offline products. Information about the CryoSat-2 products of the ICE processor can be found here:

<https://earth.esa.int/web/guest/missions/cryosat/ipf-baseline>

The following variables are used from the baseline-E Level-1b netCDF files:

Table 4: List of variables from the CryoSat-2 level-1b primary input data for the sea ice processing chain

Time-orbit data	
time_20_ku	Data record time in TAI
lon_20_ku	Longitude of measurement
lat_20_ku	Latitude of measurement
alt_20_ku	Altitude of CoG above reference ellipsoid
SIRAL waveform data	
pwr_waveform_20_ku	Normalized echo power waveform
echo_scale_factor_20_ku	Echo Scale Factor (to scale echo to watts)
echo_scale_pwr_20_ku	Echo Scale Power (a power of 2)
window_del_20_ku	Window Delay (2way) corrected for instrument delays
Instrument Flags	
flag_mcd_20_ku	Level 1b Measurement Confidence Data
Surface Type Flag	
surf_type_01	Surface type flag (1Hz, interpolated to time_20_ku)
Range Corrections	
mod_dry_tropo_cor_01	Dry Tropospheric Correction (1Hz, interpolated to time_20_ku)
mod_wet_tropo_cor_01	Wet Tropospheric Correction (1Hz, interpolated to time_20_ku)
hf_fluct_total_cor_01	Dynamic Atmosphere Correction (1Hz, interpolated to time_20_ku)
iono_cor_01	Ionosphere Correction (1Hz, interpolated to time_20_ku)
solid_earth_tide_01	Solid Earth Tide Correction (1Hz, interpolated to time_20_ku)
pole_tide_01	Geocentric Pole Tide Correction (1Hz, interpolated to time_20_ku)

5.1.2 Auxiliary Data

Auxiliary data sets are data sets that are input to the geophysical retrieval but are not a measurement of the CryoSat-2 radar altimeter. Auxiliary data sets can be static fields or data sets from satellite observations with variable temporal coverage and resolution.

5.1.2.1 Sea Ice Concentration

Daily sea-ice concentration fields at a spatial resolution of 25km is used as a sea ice mask in the sea-ice freeboard retrieval. The data source is the Global Sea Ice Concentration Climate Data Record produced by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Ocean and Sea Ice Satellite Application Facility (OSI SAF).

The data is available in from a THREDDS Data Server (TDS) of MET Norway and through the Climate Data Store (CDS) of the Copernicus Climate Change Services (C3S).

Parameter	Sea ice concentration (sea ice area fraction)
Unit	percent
Data Source	MET Norway (https://thredds.met.no/thredds/c3s/c3s.html)
Data DOI	https://doi.org/10.24381/cds.3cd8b812

The near real-time version of the thematic sea ice product uses the near real time sea ice concentration product (OSI-401-d) from OSI SAF.

Parameter	Sea ice concentration (sea ice area fraction) – Near real time
Unit	percent
Data Source	OSI SAF (https://osi-saf.eumetsat.int/products/osi-401-d)
Data DOI	https://doi.org/10.15770/EUM_SAF_OSI_NRT_2004

5.1.2.2 Sea Ice Classification

Daily sea ice classification fields at a spatial resolution of 25km from measurements of the Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I), and Special Sensor Microwave Imager/Sounder (SSMIS) sensors are ingested for the estimation of snow depth on sea ice. The sea ice classification provides an ice type flag in the categories:

1. First-year sea ice (FYI)
2. Multi-year sea ice (MYI)
3. Ambiguous
4. Unclassified

The data is available in from a THREDDS Data Server (TDS) of MET Norway and through the Climate Data Store (CDS) of the Copernicus Climate Change Services (C3S) and is produced by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Ocean and Sea Ice Satellite Application Facility (OSI SAF).

Parameter	Sea ice type (sea ice classification)
Unit	flag
Data Source	MET Norway (https://thredds.met.no/thredds/c3s/c3s.html)
Data DOI	https://doi.org/10.24381/cds.29c46d83

The near real-time version of the thematic sea ice product uses the near real time sea ice classification product (OSI-403-d) from OSI SAF.

Parameter	Sea ice type (sea ice classification) – Near real time
Unit	flag
Data Source	MET Norway (https://osi-saf.eumetsat.int/products/osi-401-d)
Data DOI	https://doi.org/10.15770/EUM_SAF_OSI_NRT_2006

5.1.2.3 Mean Sea Surface Elevation

The global high resolution mean sea surface with a spatial resolution of 1 minute from DTU Space (Version DTU21) is used to facilitate the estimation of sea-level along the ground-track of CryoSat-2. This data set is static and used for the entire CryoSat-2 data record.

Parameter	Elevation of mean surface
Unit	meter
Data Source	DTU-SPACE (https://ftp.space.dtu.dk/pub/DTU21/1_MIN/)

5.1.2.4 Climatology of Snow Depth on Sea Ice

The estimation of snow depth is partly based on a monthly snow depth climatology described in Warren et al., 1999, hereafter referred to as the W99 snow depth climatology. The climatology is available as two-dimensional quadratic fit coefficients that can be used to compute values of snow depth, density, and variability for given geographical coordinates. The domain of validity for W99 is the central Arctic basin. See section 5.2 for a full description of snow on sea ice data.

5.1.2.5 Passive Microwave Observations of Snow Depth on Sea Ice

Additional input to the snow depth retrieval algorithm in the sea ice processor are daily snow depth fields on Arctic sea ice from passive microwave observations from Advanced Microwave Scanning Radiometer 2 (AMSR2) produced by the Institute of Environmental Physics (IUP) of the University Bremen. Snow depth retrieval from AMSR2 data is based on the work of Markus and Cavalieri, 1998 and only valid over first-year sea ice. It must be noted that a newer version of the IUP data set is currently available (Rostosky et al., 2018), compared to the version 1.0 used for the snow depth climatology in the Cryo-TEMPO sea ice product.

5.1.2.6 Sea Ice Regions

5.1.2.6.1 Arctic

The 2021 version of the regional mask for Arctic sea ice trends and climatologies defines commonly used regions relevant for Arctic sea ice as polygons for each region (Scott Stewart and Walter N. Meier, NSIDC). The region definition was supplied by NSIDC in shapefile format and the id number of each region has been gridded on an EASE2 grid with a resolution of 1 km (Figure 4 and Table 5). The region id is added to each freeboard and snow depth value along the CryoSat-2 ground track to allow easy assessment of sea ice results by region.

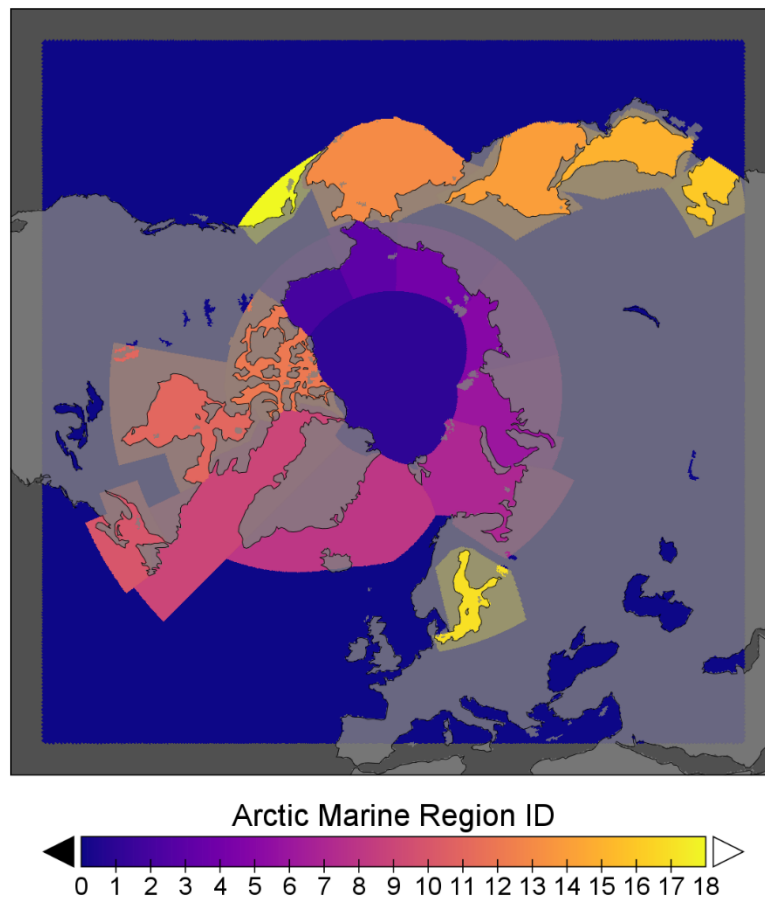


Figure 4: Map of region id's from the 2021 version of the regional mask for Arctic sea ice trends and climatologies (credit J. Scott Stewart and Walter N. Meier, NSIDC).

Table 5: Region id's and their name from the 2021 version of the regional mask for Arctic sea ice trends and climatologies (credit J. Scott Stewart and Walter N. Meier, NSIDC).

ID	Region Name	ID	Region Name
0	Undefined Region	10	Gulf of St. Lawrence
1	Central Arctic	11	Hudson Bay
2	Beaufort Sea	12	Canadian Archipelago
3	Chukchi Sea	13	Bering Sea
4	East Siberian Sea	14	Sea of Okhotsk
5	Laptev Sea	15	Sea of Japan
6	Kara Sea	16	Bohai Sea
7	Barents Sea	17	Baltic Sea
8	East Greenland Sea	18	Gulf of Alaska
9	Baffin Bay & Labrador Sea		

5.1.2.6.2 *Antarctic*

The region codes in the southern hemisphere are based on longitude sectors after Parkinson and Cavalieri, 2012. The maximum latitude for all regions is 40S.

Table 5: Definition of sea ice regions in the southern hemisphere.

Code	Region Name	Longitude Bounds
100	Indian Ocean	20.0 : 90.0
101	Western Pacific Ocean	90.0 : 160.0
102	Ross Sea	160.0 : -130.0
103	Bellingshausen and Amundsen Seas	-130.0 : -60.0
104	Weddell Sea	-60.0 : 20.0

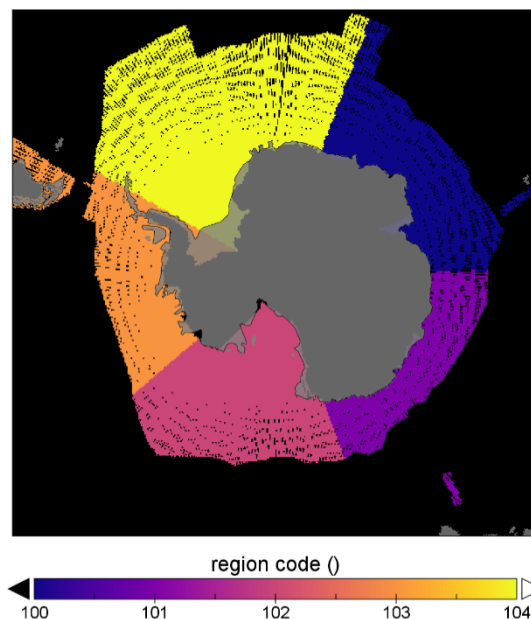


Figure 5: Example of sea ice regions codes for all SAR and SARin data the Southern Ocean.

5.1.2.7 High resolution land mask

A gridded land-ocean mask for the Arctic regions at a resolution of 250 m has been created based on shapefiles of the OpenStreetMap¹ project except for the landmass of Greenland, which is sourced from the Natural Earth project². The reason for the two-source solution is a better agreement of the Natural Earth shapefile with the Greenland topography from Global 30 Arc-Second Elevation (GTOPO30) digital elevation model, while the OpenStreetMap shapefiles provide more detail in the rest of the Arctic. This data set is not used in the Antarctic region.

5.2 Snow Depth on Sea Ice

Snow depth on sea ice is a geophysical parameter that is not measured at the same spatial coverage and resolution of the CryoSat-2 radar altimeter data. A consistent snow depth data source for the entire CryoSat-2 data record can therefore only be obtained from a climatology or the result of numerical simulations that model snow accumulation on sea ice based on precipitation from reanalysis data.

5.2.1 Arctic Sea Ice

The Cryo-TEMPO thematic winter sea ice product utilizes the climatology approach, based on data fusion of the W99 climatology (see section 5.1.2.4) with passive microwave data (see section 5.1.2.5)

¹ <https://www.openstreetmap.org/>

² <https://www.naturalearthdata.com/>

to overcome the individual limits of both data sets, namely the regional limit of the W99 sea ice climatology and the FYI limitation of the passive microwave data.

The merged climatology is computed monthly between October and April for the application to the Arctic winter season. The merged climatology is static for these months and the data is ingested as an auxiliary data file into the sea ice processor. The monthly files can be downloaded from the following ftp site:

ftp://ftp.awi.de/sea_ice/auxiliary/snow_on_sea_ice/w99_amsr2_merged/

This section provides a description of how the data sources were merged and how the data is used in the sea ice processor.

5.2.1.1 Data Fusion of Climatology and Satellite Data

To merge the two data sources, monthly composites by averaging daily IUP AMSR2 snow depth fields have been created to match the monthly resolution of the W99 climatology for October to April. A low pass filter is applied to the IUP AMSR2 snow depth composite to remove artefacts associated to specific ice conditions using a Gaussian filter with the size of 8 grid cells (50km). In additions, spurious negative snow depth values are removed, and the upper snow depth range is limited to 60 cm.

The principal objective is to use the W99 climatology in the central Arctic Basin and the filtered monthly composite in the remaining sea ice covered marine areas of the northern hemisphere. To ensure continuity between the two domains, a regional weight factor w is computed based on a regional mask based on the assumed validity of the W99 climatology. The mask consists of the central Arctic Basin with a weight factor w of 1 indicating full validity of W99 snow depth information. Outside the central Arctic Basin, the weight factor is reduced to 0 over a distance of 250 km (Figure).

The monthly merged snow depth climatology sd_{merged} is computed as:

$$sd_{merged} = w \cdot sd_{W99} + (1 - w) \cdot sd_{AMSR2}$$

See Figure for visual examples of the merging steps.

It is however common practice to modify the W99 snow climatology by reducing its value by 50% over first-year sea ice in the central Arctic. We therefore use the sea ice type auxiliary data set (section 5.1.2.2) to modify the climatology along each orbit trajectory. The sea ice type data is used in the sense of multi-year ice fraction (f_{myi}) with a value between 0 (100% FYI) and 1 (100% MYI). The result is the snow depth on sea ice (sd), or surface snow thickness, of the Cryo-TEMPO thematic sea ice product. The reduction is only applied for the W99 contribution to the merged snow depth value resulting in following approach where $c_{fyi}=0.5$ is the W99 scaling for first-year sea ice, c the total scaling factor that includes the multi-year sea ice fraction f_{myi} and the weight factor:

$$c = (1 - f_{myi}) * c_{fyi} * w$$

$$sd = sd_{merged} - c \cdot sd_{merged}$$

5.2.1.2 Uncertainty

The snow depth uncertainty is computed like the computation steps in the previous section. All input data sets provide an uncertainty value, the AMSR2 provides a spatially variable retrieval uncertainty (σ_{sd}^{AMSR2}) and the W99 climatology provides interannual variability as uncertainty (σ_{sd}^{W99}) and the sea ice type a retrieval uncertainty ($\sigma_{f_{myi}}$).

$$\sigma_{sd}^{merged} = w \cdot \sigma_{sd}^{W99} + (1 - w) \cdot \sigma_{sd}^{AMSR2}$$

$$\sigma_{sd} = \left(\sigma_{sd}^{merged} - c \cdot \sigma_{sd}^{merged} \right) + \left(sd \cdot c \cdot \sigma_{f_{myi}} \cdot c_{fyi} \right)$$

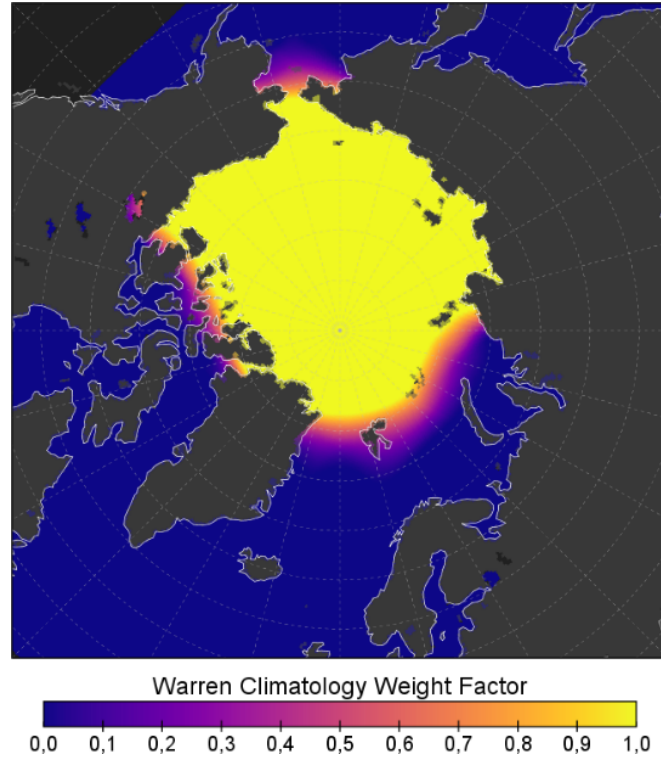


Figure 6: Regional W99 snow climatology weight factor w

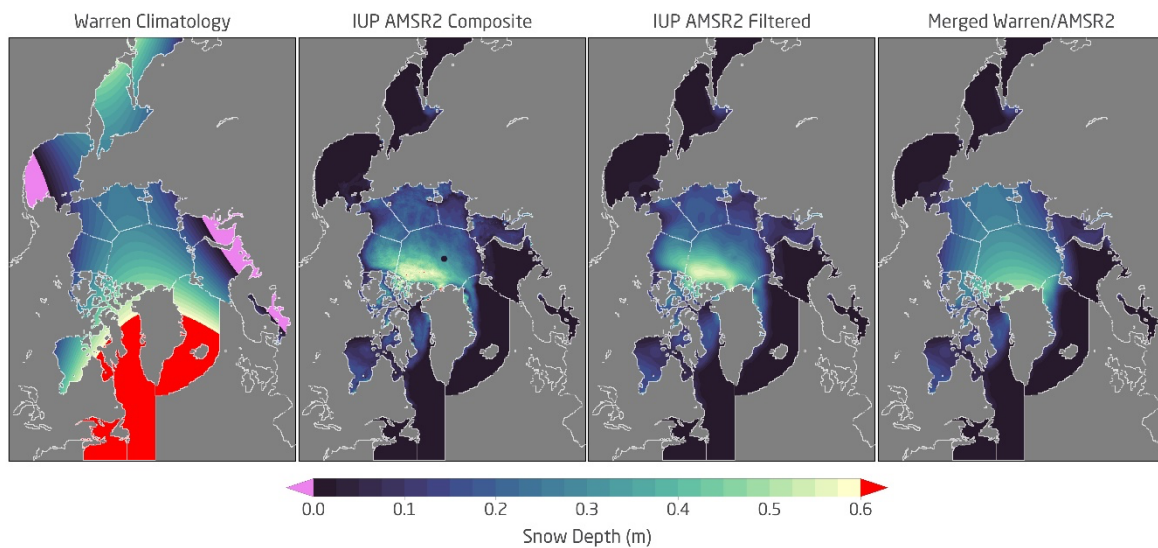


Figure 7: Snow depth data fusion for monthly climatology based on W99 climatology and monthly averaged data from AMSr2 (IUP Bremen).

5.2.2 Antarctic Sea Ice

The snow depth data set used for the southern hemisphere is the ESA CCI Antarctic snow depth dataset generated by the Integrated Climate Center of the University of Hamburg^[1].

The data set contains a daily climatology of snow depth on Antarctic sea ice from AMSR-E brightness temperatures using the algorithm described in Markus and Cavalieri (1998). A full description of the algorithm and dataset is given in Kern et al. 2015.

Figure 8 illustrates the monthly average snow depth fields. The retrieval algorithm utilizes the daily resolution of the snow depth climatology.

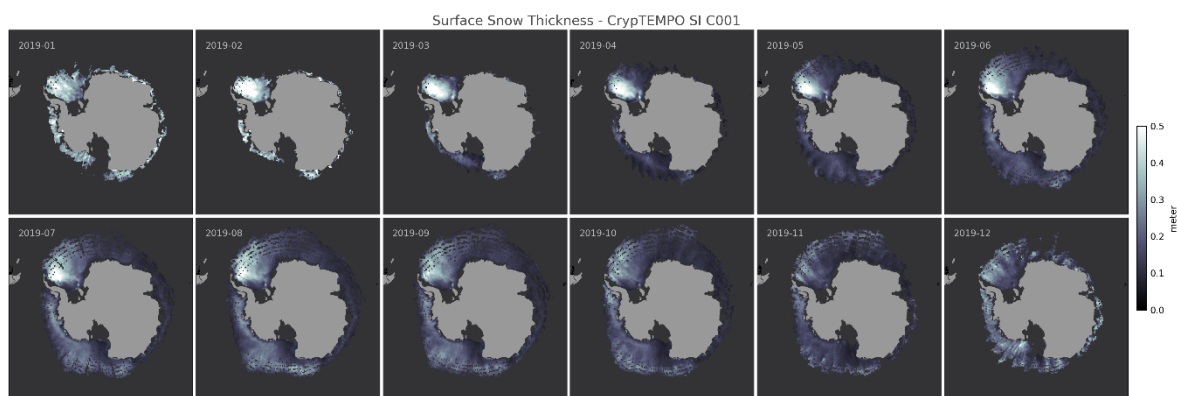


Figure 8: Monthly snow depth climatology in the southern hemisphere (Kern et al., 2015).

^[1] <https://www.cen.uni-hamburg.de/en/icdc/data/restricted-access/esa-cci-antarctic-snow-depth.html> (last accessed January 2024)

5.3 Sea Ice Freeboard

This section describes the sea-ice freeboard processing chain with input from all auxiliary data and the snow depth data described in Section 5.2.

5.3.1 Pre-processing of Level-1b data

A regional subset of latitudes higher than 45 degrees North is used to limit the available CryoSat-2 L1b SAR and SARin data. For these two subsets, all data files of a one orbit are merged into a single orbit segment, since input data may be distributed into different files based on the radar mode. The objective is to create a continuous data segment over marine areas. Longer data segments over land are cropped from the data set (see Figure for an example).

The subsetting to the Arctic Ocean domain is based on the high resolution land/ocean mask, which replaces the surface type mask included in the CryoSat-2 L1b data (variable `surf_type_01`).

In addition, waveform shape parameter used for surface type classification (Section 5.3.2) is computed, the timestamp is converted from TAI to UTC and the merged L1b data subset is stored in of processing level 1-preprocessed (L1p) internally on the production system.

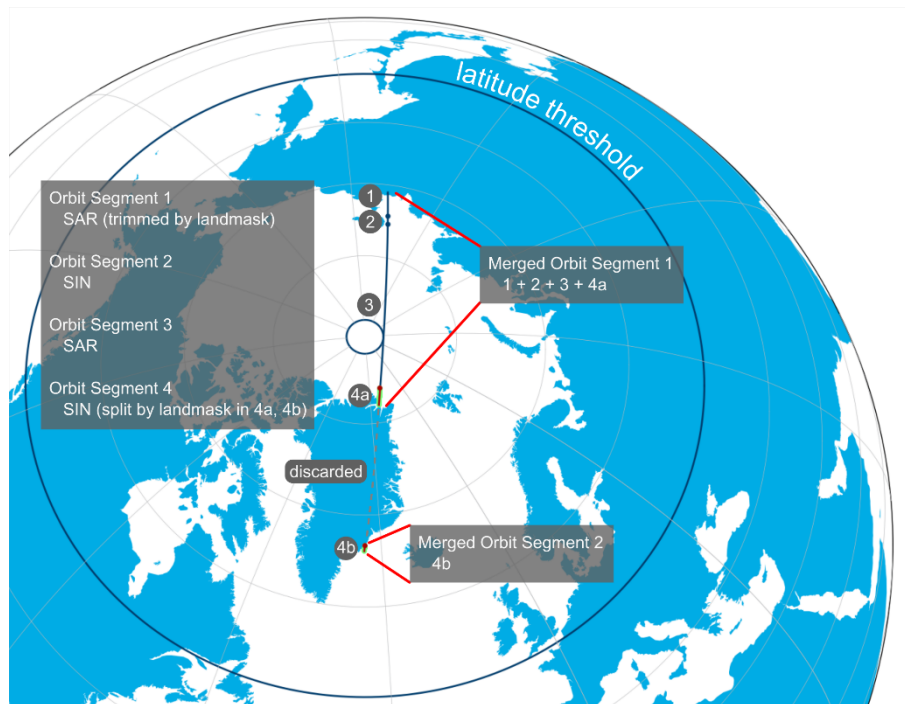


Figure 9: Exemplary radar data selection and merging process of SAR and SARin data

5.3.2 Surface Type Classification

The first step in the sea-ice freeboard retrieval is the surface type classification for each waveform based on pre-computed waveform shape parameters. The objective is assigning each waveform one of the four classification values:

1. Open ocean: Measurement over water surfaces outside the sea ice cover.
2. Lead: Measurement over water surfaces inside the sea ice cover between sea ice floes or at sea ice fractures.
3. Ice Surface: Measurements that solely consist of sea ice surfaces.
4. Ambiguous: Measurements from mixed surfaces or where the classification has failed

The surface type classification algorithm originates from the most recent algorithm development in the ESA Climate Change Initiative – Sea Ice Project and classifies waveform based on four waveform parameters:

1. Pulse Peakiness (PP)
2. Leading Edge Width (LEW)
3. Leading Edge Quality (LEQ)
4. Radar backscatter coefficient (SIGMA0)

The pulse peakiness PP is computed based on the power of each range bin WF_i , the maximum power of the waveform $\max(WF)$ and the number of range bins N_{wf} in the waveform:

$$PP = \sum_{i=1}^{N_{wf}} \frac{\max(WF)}{WF_i} \cdot N_{wf}$$

The leading-edge width LEW is computed using the TFMRA retracker algorithm (see section 5.3.3.2) for power thresholds of 5 and 95%. The leading edge quality is defined as the cumulative power raise until the first maximum, divided by the first maximum power. A monotonically increasing leading edge has LEQ value of 1. Values greater than 1 indicate noise on the leading edge and waveforms with large LEQ waveforms should be rejected.

$$LEQ = \frac{\sum_{i=2}^{FMI} (WF_i - WF_{i-1})}{WF_{FMI}}$$

The radar backscatter coefficient is computed after Dinardo, 2016.

The thresholds for the three parameters have independent values for SAR and SARin waveforms. In addition to the waveform-based classification, the sea-ice concentration data is providing the daily sea-ice mask and the land/sea flag (variable surf_type_01) from the L1b input data set is used to exclude any data over land. The land/sea flag is provided at 1Hz in the L1b files and its values is replicated to all 20Hz waveforms within the 1 second window.

After classification, the surface type flag is merged with the land/sea flag for further use in the processor into a single flag container that contains the external mask-based land/ocean information and the ice/water flag from the waveform-based classification. The classification is used for both Arctic and Antarctic regions.

5.3.2.1 Open Ocean

Measurements over open ocean are mainly classified by the sea-ice concentration auxiliary data set and the land/sea flag: Every waveform that is marked as ocean (variable `surf_type_01` is 0) and where the sea ice concentration is below 15%, a threshold used for the ice edge in sea-ice concentration data sets from passive microwave observations. Since isolated patches of sea ice exist in areas with sea ice concentrations lower than 15%, the homogeneity of the surface is tested using the variability (standard deviation) of the pulse peakiness in a rolling 25 km window.

Table 6: Parameter thresholds for the classification of open ocean surfaces in CryoSat-2 SAR and SARin data.

Surface Type	Radar Mode	Parameter	Condition
Open Ocean	SAR	Sea Ice Concentration	< 15%
		PP rolling standard deviation	< 1
	SARin	Sea Ice Concentration	< 15%
		PP rolling standard deviation	< 4

5.3.2.2 Lead Surface

Radar altimeter measurements over leads within the sea ice cover are characterized by specular reflection, resulting in narrow echoes with a high peak power. To be classified as a lead waveform, PP and SIGMA0 must exceed a minimum threshold, while LEW must be smaller than a maximum threshold. The following parameter thresholds are valid for Arctic sea ice in the winter period between October and April and all month in the Antarctic.

Table 7: Parameter thresholds for the classification of lead surfaces in CryoSat-2 SAR and SARin data.

Surface Type	Radar Mode	Parameter	Condition
Lead	SAR	Sea Ice Concentration	$\geq 15\%$
		PP	≥ 66.0
		SIG0	≥ 23.0
		LEW	≤ 0.75
	SARin	Sea Ice Concentration	$\geq 15\%$
		PP	≥ 260.0
		SIG0	≥ 24.0
		LEW	≤ 1.05

5.3.2.3 Sea Ice Surfaces

All waveforms within the sea ice mask that have not been classified as lead waveforms are considered to be sea ice waveforms. This approach has been chosen to achieve realistic sea ice waveform detection rates in thin ice areas. Only a quality control of the leading edge using the LEQ parameter is applied to filter noisy waveforms.

Table 8: Parameter thresholds for the classification of sea ice surfaces in CryoSat-2 SAR and SARin data.

Surface Type	Radar Mode	Parameter	Condition
Sea Ice	SAR	Sea Ice Concentration	$\geq 15\%$
		LEQ	≤ 1.02
		Surface Type	is not class Lead
	SARin	Sea Ice Concentration	$\geq 15\%$
		LEQ	≤ 1.02
		Surface Type	is not class Lead

5.3.2.4 Ambiguous Surfaces

All waveforms that are not classified as one of the other surface types or as land by the land/sea flag are designated as ambiguous and discarded from further processing.

5.3.3 Retracker Algorithm

A retracking algorithm determines the range from the spacecraft altimeter sensor to the dominant backscatter surface, as several backscatter sources may contribute to a single radar waveform.

The retracker choice depends on the product type. The regular thematic sea ice product is based on the SAMOSA+ retracker (section 5.3.3.1), while the near real-time version uses the faster TFMRA (section 5.3.3.2).

5.3.3.1 SAMOSA+ Retracker

The SAMOSA+ retracker is a SAR Altimetry retracker designed for open ocean surfaces based on the stack range integrated power (RIP) (Dinardo et al., 2021). In the frame of Cryo-TEMPO a special Python implementation of the SAMOSA+ retracker is developed from L1B³. The main formulation of the code can be found in the ATBD for Coastal Ocean.

³ <https://github.com/pysiral/samosa-waveform-model> (last accessed October 2024)

For the sea ice product, the SAMOSA+ code deviates from the Coastal Ocean theme by several points. Therefore, the SAMOSA+ waveform fitting depends on a dedicated implementation of the SAMOSA+ waveform model⁴.

- The sea ice algorithm uses CrySat-2 L1b ICE data as input, compared to the Geophysical Ocean Product (GOP) in the Coastal Ocean product.
- The Hamming Function is activated for the ICE product.
- The stack zero-mask (as computed at L1b) is provided in the L1b products.
- The SAMOSA+ waveform model for sea ice waveforms is fitted to a sub-waveform and not all range gate power values. Peaks at the trailing edge originating from off-nadir backscatter targets are identified and removed from the waveform fitting process. The sub-waveform filtering process is described below, and visual examples is given in Figure .
- The estimation of the waveform epoch in the fitting process partially depends on the initial guess and pre-defined fit bounds defining the valid range of epoch values. Both initial guess and fit bounds are based on the first maximum and not the main maximum of the waveforms. This is done in combination with the sub-waveform filter (previous point) that the waveform model fits the main sea ice class in mixed sea ice conditions and is not biased by off-nadir backscatter targets.
- The impact of the significant wave height parameter for specular lead waveforms is low. This parameter is set to zero and removed from the free fit parameters in the waveform fitting process.

For sea ice waveforms the trailing edge is first cleaned by off-nadir peaks. This process follows the following steps:

1. Identification of trailing edge defined as all range gates after the first maximum
2. Computation of relative minima using the function `argrelemin` of the python `scipy` package
3. Iterative cleaning of relative minima in 5 passes: No minima should have a higher power than the previous minima
4. Selection of all range gate power values that are within the defined noise distance within the linear fit between remaining minimal.
5. All range gate power values that are not within the noise limit are rejected.

The SAMOSA+ retracker model is then applied to all lead (Figure 10) and sea ice waveforms (Figure 11). The following output parameters are computed.

1. Epoch / Range to the mean of the surface elevation distribution with range uncertainty.

⁴ <https://github.com/pysiral/samosa-waveform-model> (last accessed, September 2024)

2. Significant wave height with uncertainty. This parameter is converted to surface elevation standard deviation by division of significant waveheight with factor 4.
3. Mean square slope: Smaller scale roughness with impact on backscatter.
4. SAMOSA+ waveform model misfit of total waveform.
5. SAMOSA+ waveform model misfit of sub-waveform.

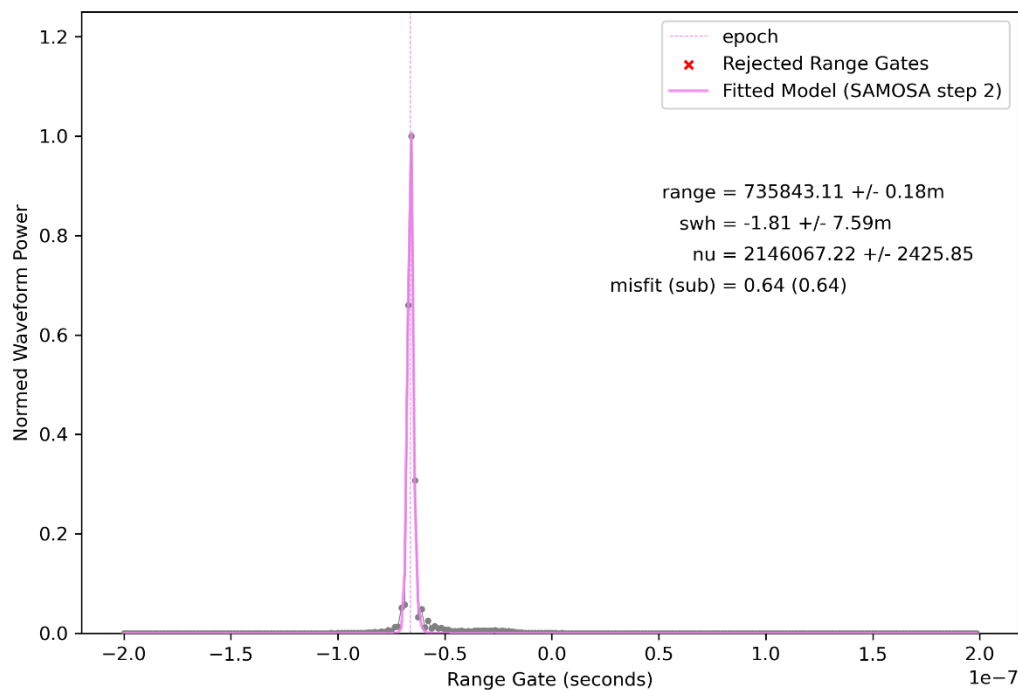


Figure 10: Lead waveform (line with circle markers) and SAMOSA+ waveform model (violet line). Vertical line represents the epoch.

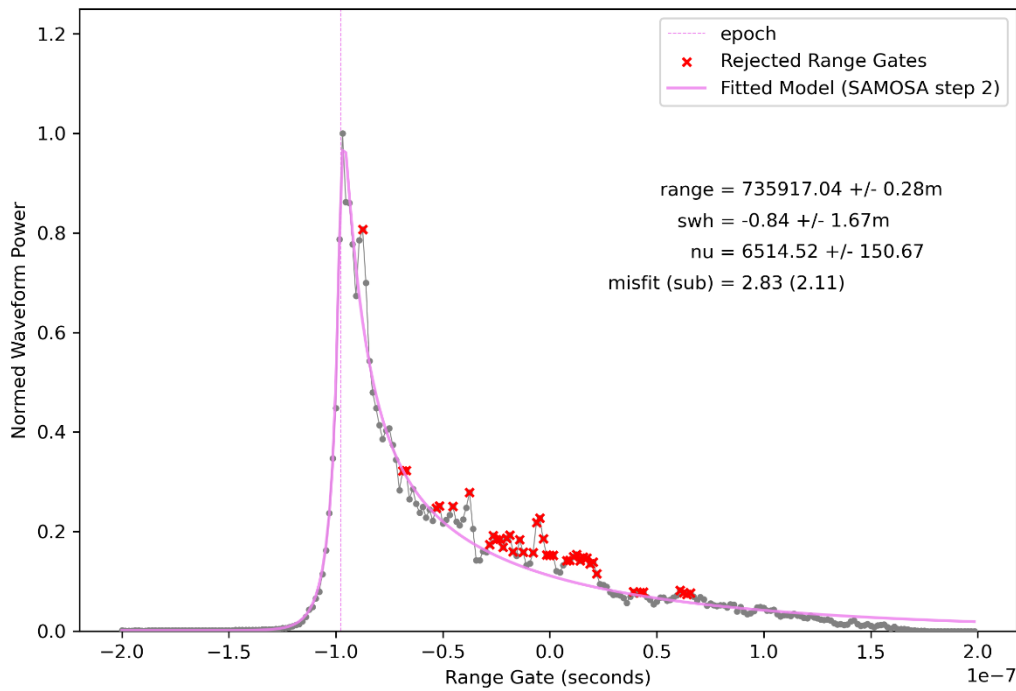


Figure 11: Example of sea ice waveform (line with circle markers) with moderate to weak off-nadir backscatter peaks (red crosses) and SAMOSA+ waveform model (violet line). Vertical line represents the epoch.

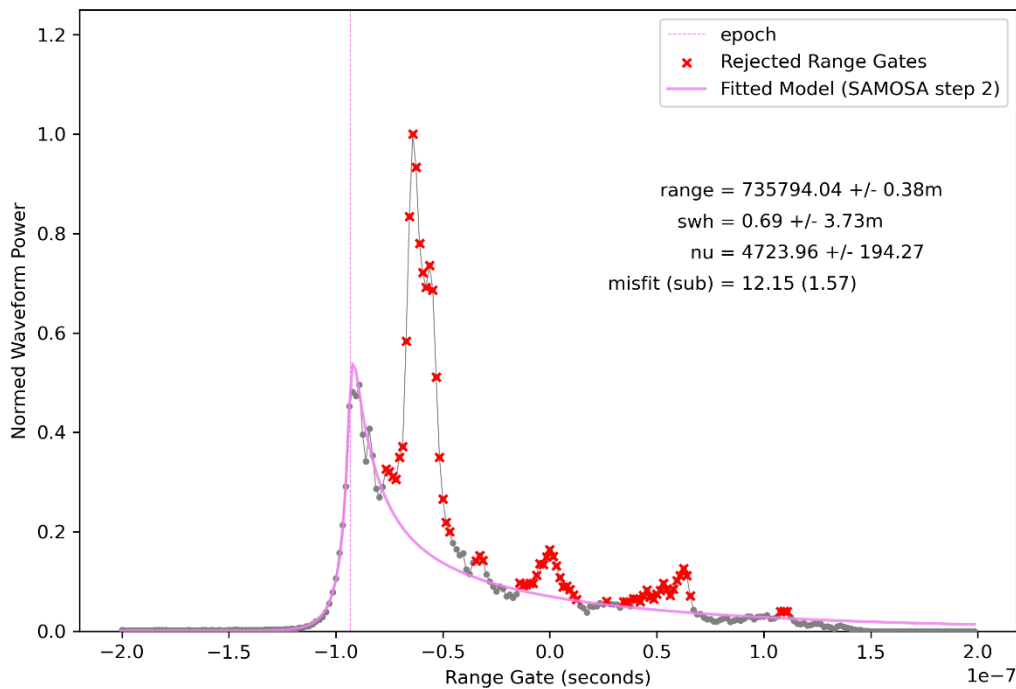


Figure 2: Example of sea ice waveform (line with circle markers) with substantial off-nadir backscatter peaks (red crosses) and SAMOSA+ waveform model (violet line). Vertical line represents the epoch.

5.3.3.2 Threshold First Maximum Retracker Algorithm (TFMRA)

For lead and sea ice surfaces it is assumed that the range to the surface is located on the leading edge at the half-power point (power threshold) of the first significant maximum of the waveform. This retracker is used only for the near-real time version of the Cryo-TEMPO winter sea ice thematic product.

The specific TFMRA implementation used in Cryo-TEMPO is oriented after the implementation used in Ricker et al., 2014. The algorithm only depends on the leading edge of the waveform before the first maximum. The algorithm to determine the range at the leading edge when the power level has crossed a certain threshold can be implemented in robust and numerical efficient way. But as also shown by Ricker et al., 2014, the results over sea ice are critically dependent on the power threshold values for both lead and sea ice waveforms. The thresholds for lead (50%) and sea ice surfaces (50%) used here originate from the ESA Climate Change Initiative sea ice project and have been chosen due to a better representation of the seasonal cycle of Arctic sea ice thickness than alternative fixed threshold parametrizations, e.g., by setting both power thresholds for water and ice surfaces to 80% (Khvorostovsky et al., 2020).

CryoSat-2 waveforms are sampled in discrete intervals at a resolution of 0.2342m for SAR and SARin radar modes that can be coarse for the narrow waveforms of lead respectively smooth and undeformed sea ice. The TFMRA implementation there uses a filtered representation of the sampled waveforms from the L1B data to counter the aliasing effect. The filtering parametrization differs for SAR and SARin waveforms to account for the different noise level of the two radar modes.

Specifically, the following processing steps are executed by the TFMRA implementation:

1. Waveform oversampling by a factor of 10 using linear interpolation of the L1B waveform power.
2. Smoothing of the oversampled waveform using a box filter with the width of 11 points for SAR waveform and 21 points for SARin waveforms. The reason for a larger smoothing of SARin waveforms is higher noise levels.
3. Normalizing of the filtered waveform power (maximum power has the value of 1.0).
4. Detection of the first maximum on the filtered and normed waveform power as the first point that exceeds the value of 0.15 for SAR and 0.45 for SARin waveforms
5. Estimation of the position within the range window with a rise to 50% of the power of the first maximum by linear interpolation between the two closest points of the filtered waveform.
6. TFMRA retracker range is then computed by adding position within the range window to the window delay corrected for center of mass and other corrections (variable `window_del_20_ku` in the L1B file).

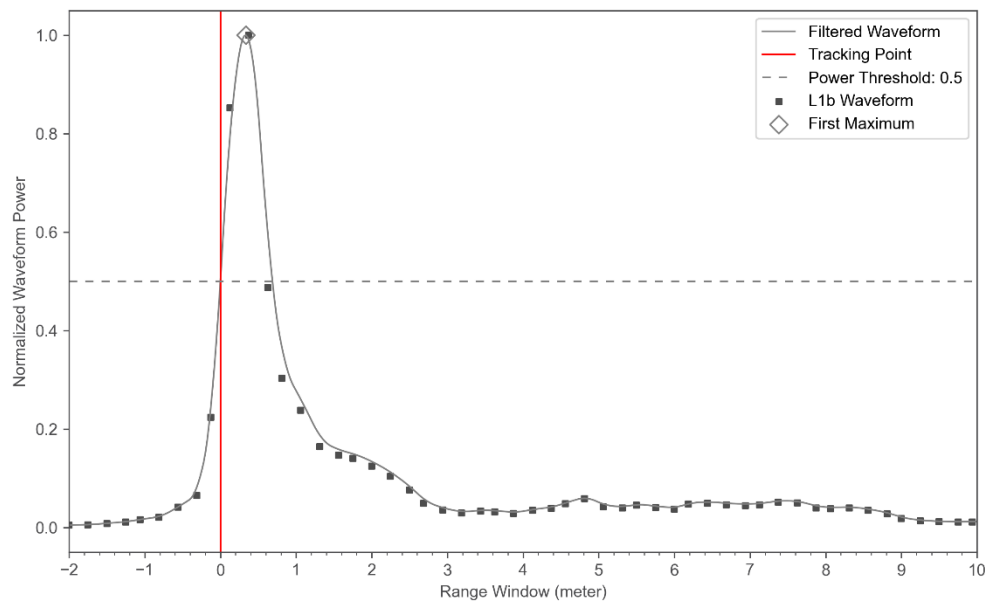


Figure 513: Schematic of the TFMRA implementation. The retracking point is estimated when the filtered waveform exceeds a power threshold at the leading edge.

TFMRA Algorithm Parameter	Value
Waveform Oversampling Factor	10
Smoothing box filter size (oversampled range bins)	11 SAR / 21 SARin
First Maximum normalized power threshold	15% SAR / 45% SARin
Retracker power threshold	50% (for all surface types and radar modes)

Each waveform identified as either lead or sea ice by the surface type classification is retracked by TFMRA with a 50% power threshold. The retracker returns the location of the surface within the range window of the full waveform. This information is then used to compute the range r from the center of mass of the spacecraft to the surface by adding the window delay (variable `window_del_20_ku`). The window delay refers to the two-way time of the transmitted and received radar pulse with respect to the center of the waveform range windows and is already corrected for instrument delays. The two-way time is converted into range using the speed of light in vacuum.

The TFMRA algorithm does not provide an uncertainty value, therefore it is parametrized with 0.1m. This value has been empirically derived by evaluating the standard deviation over larger stretches of thin and presumable flat sea ice.

5.3.4 Surface Elevations and Range Corrections

The TFMRA range r and the altitude of the center of gravity of the spacecraft h_{cog} provide information of the surface elevation $h_{surface}$ with respect to the reference ellipsoid. At this stage, the range has been computed based on the speed of light in vacuum and corrections need to be applied for varying wave propagation speed depending on the condition of the troposphere and ionosphere. In addition,

tidal corrections are applied to range for consistency of elevations of ocean surfaces for different data acquisitions:

$$h_{surface} = h_{cog} - r + \sum r_c$$

The list of range corrections r_c is the following:

- Ionosphere correction (source: L1b)
- Dry troposphere correction (source: L1b)
- Wet troposphere correction (source: L1b)
- Dynamic atmosphere correction (source: L1b)
- Elastic ocean tide (source: FES2022)
- Long-period ocean tide (source: FES2022)
- Ocean loading tide (source: FES2022)
- Solid earth tide (source: L1b)
- Geocentric polar tide (source: L1b)

There are two data sources for the different range correction: Corrections for range effects caused by conditions in the ionosphere, troposphere as well as the dynamic atmosphere correction, which combines the inverse barometric effect with the high-frequency fluctuations of the ocean surface. These parameters and the solid earth tide and polar tide are based on information present in the Level-1b primary input data (see section 5.1.1). The remaining tidal corrections are sourced from the more recent and RegAT-Arctic regional model (Cancet et al., 2022, in prep.).

5.3.5 Sea Surface Anomaly and Radar Freeboard

After application of the range correction, the surface heights split into two categories, the heights of lead surfaces and the heights of sea ice surfaces.

The heights of the lead surfaces with respect to the mean sea surface (mss) yield raw observations of the sea level anomaly (sla_{raw}) at discrete locations where the surface type classification indicates the presence of a lead:

$$sla_{raw} = h_{surface}[surface\ type \equiv\ lead] - mss$$

The discrete sea-level anomaly observations must be extended to all ice surfaces as reference for the ice surface heights. This is achieved by an interpolating and smoothing function that provides a continuous sea level anomaly (sla):

$$sla = func(sla_{raw})$$

The function contains several main processing steps:

1. Smooth sla_{raw} with a box filter with filter size of 100km to reduce the raw noise of the observations. This step is only applied to the existing observations. The filter size width has been chosen empirically as a compromise in reducing noise and retaining true spatial variability of the sea surface height.
2. Apply a linear interpolation between the smoothed raw sea-level anomaly observations for the entire trajectory.
3. Apply a box-filter smoother to the interpolated values with the same filter size as before (100 km).
4. Set the result to NaN (not a number) if the closest sla_{raw} observation is not within two times the filter size (200km).

The output is a smoothed and interpolated sea-level anomaly (sla) that extends along the entire ice-covered area if enough leads are present.

The uncertainty of this approach is parametrized with the following formular and based on the distanced_{tp} to the next sla_{raw} tie point. The uncertainty increases with distance to raw sea-level anomaly observations and reaches its maximum at 100km. The uncertainty reaches its minimum at the location of a raw sea-level anomaly observation, and it is assumed that the smoothing process results in an uncertainty of 0.02 m:

$$\sigma_{sla} = \begin{cases} 0.02m + 0.1m \times \left(d_{tp}/100km\right)^2, & d_{tp} < 100km \\ 0.1m, & d_{tp} \geq 100 km \end{cases}$$

Subtracting the sum of sea level anomaly and mean sea surface from the sea ice heights h_{ice} then yield radar freeboard f_{radar} . The parameter is defined as the freeboard as measured directly by the radar altimeter from range differences of ice surfaces and the local sea level without further corrections or use of auxiliary data sets.

$$\begin{aligned} h_{ice} &= h_{surface} [surface\ type \equiv sea\ ice] \\ f_{radar} &= h_{ice} - (mss + sla) \\ &= h_{ice} - ssh \end{aligned}$$

The radar freeboard uncertainty is then defined as:

$$\sigma_{f_{radar}} = \sqrt{\sigma_{h_{ice}}^2 + \sigma_{sla}^2}$$

with the assumption that the mean sea surface uncertainty is included in the sea level anomaly uncertainty and a fixed value for the uncertainty of the sea ice heights ($\sigma_{h_{ice}}$) currently set to 0.1m for the range derived from both TFMRA and SAMOSA+ retracker.

5.3.6 Sea Ice Freeboard

Radar freeboard differs from sea-ice freeboard by a range correction that takes the slower wave propagation speed in the snow layer into account. Without this correction and in the presence of a significant snow layer, the radar freeboard underestimates the true sea-ice freeboard f_{ice} :

$$f_{ice} = f_{radar} + \Delta r_{snow}$$

The range correction depends both on the snow depth sd that controls the affected fraction of the travel path as well as the snow density ρ_s , which controls the wave propagation speed in the snow layer c_s that differs from vacuum lightspeed c :

$$\Delta r_{snow} = \left(\frac{c}{c_s} - 1 \right) \cdot sd$$

$$c_s = c (1 + 0.51 \times \rho_s)^{-1.5}$$

The density of snow on sea ice is increasing throughout the winter season and it is parametrized as a function of time t that is represented the elapsed fractional month since October 15:

$$\rho_s = 6.5 \times t + 274.51$$

The source for the computation of the Δr_{snow} is Mallet et al., 2020. There is no uncertainty information for the snow density parametrization, so the sea-ice freeboard uncertainty is computed based on the uncertainties of the radar freeboard and snow depth:

$$\sigma_{fice} = \sqrt{\sigma_{f_{radar}}^2 + \left(\frac{c}{c_s} - 1 \right)^2 \cdot \sigma_{sd}^2}$$

5.3.7 Filtering

5.3.7.1 Radar Freeboard Filter

Radar freeboards derived from SAMOSA+ waveform fit with high sub-waveform misfit and larger uncertainty are set to not-a-number (NaN). This applies to radar freeboard values if one of the following conditions apply.

1. Value not within the valid range from -0.5 to 2.5 m
2. Sub-waveform misfit is greater than 5
3. The leading-edge model error is greater than 0.1

The leading-edge model error is defined as the root mean square error of between waveform and waveform mode between the first range bin where the waveform model raises above a factor of 0.005 of the model peak power and the peak-power location. This metric is designed to detect so-called “snagging”, e.g when the waveform main peak originates from an off-nadir position. Radar freeboards from these waveforms are often associated with strongly negative freeboards.

5.3.7.2 Sea Ice Freeboard Filter

Sea-ice freeboard values outside the range of -0.25 to 2.25 meter are removed and set to not-a-number (NaN) to exclude unrealistic observations due to a misclassification or surface targets that are not sea ice, e.g., icebergs. The NaN mask of the sea-ice freeboard is then also applied to radar freeboard, to keep the two variables consistent.

5.3.7.3 Marginal Ice Zone Flag

Sea ice freeboard values in the marginal ice zone, especially in the southern hemisphere are often influenced by ocean swell penetrating the ice pack. The impact on radar freeboard differs between retracker algorithms. The SAMOSA+ retracker mainly mitigates the biasing impact on sea ice freeboard, while the TFMRA in the near real-time product is substantially biased high in the case of surface waves.

Impacted waveforms are flagged, but not sea ice freeboard values are not removed. This is motivated by allowing the extraction of geophysical information from the affected records. #The application of a removing filter is the responsibility of the user.

The method of computing the flag differs between the regular and near real-time thematic sea ice product due to the different retracker algorithms. For the TFMRA-based near real-time product there is a distinction of two different cases.

5.3.7.3.1 SAMOSA+ - significant wave height threshold

The marginal ice zone filter flag for the regular thematic product uses the significant wave height parameter of the SAMOSA+ retracker and the proximity to the ice edge, which is computed from the sea ice concentration field. Specifically, all waveforms inside the sea ice cover with significant wave height estimates higher than 3.2 m and an ice edge proximity of less than 150 km are flagged as potentially influenced by ocean swell.

5.3.7.3.2 TFMRA - Open Ocean to sea ice transition

In this case, an orbit trajectory passes from open ocean into the sea ice cover or vice versa. Multiple transitions per orbit segment are also possible. Each of the transitions are detected and for each the following computations are made:

Compute the distance to ocean. This is done based on the gridded sea ice concentration data, as the trajectory might run oblique to the ice edge. The distance to ocean can only be computed with a granularity of the spatial resolution of the sea ice concentration data.

1. Compute average leading-edge width of open ocean waveforms for the first 25 km of open water
2. Compute the sea ice freeboard gradient with a smoothing window of 150 km
3. Conditions for the settings the MIZ filter flag:

Filter Flag	Condition
-------------	-----------

True (1)	Main requirement: Open ocean average leading edge with > 2.5 or Sea ice freeboard gradient at ice edge > 0.2 m/km If one of the requirement are met, the filter value for all waveforms is set to 2 until the first occurrence where the sea ice freeboard gradient reaches 0 m / km
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5.3.7.3.3 TFMRA - Open Ocean Proximity

There are cases where the freeboard is impacted by surface waves in the proximity of the ice edge, but the trajectory does not cross into open water. The filter setup from the previous subsection is not suitable for such a case.

Rather, a set of parameter thresholds is used to set filter flag values:

Filter Flag	Condition
True (1)	All conditions must be met: 1. Sea Ice Concentration $\leq 75\%$ 2. The distance to ocean (determined by sea ice concentration) ≤ 300 km 3. Rolling mean of leading-edge width (25 km window) ≥ 2.0 4. Rolling standard deviation (25 km window) of pulse peakiness ≤ 15.0

5.4 Gridded Level-3 Data

This section describes how the orbit-based Level-2 data is mapped onto spatiotemporal grids resulting in gridded (processing level 3) data. This step does not include interpolation, but Level-2 data points are strictly referenced to a single grid cell. An example of gridded sea ice freeboard is shown in Figure 15.

5.4.1 Temporal Coverage

Data is gridded periods between October 1st and April 30th of each winter season in the northern hemisphere and for all months in the southern hemisphere. Specifically, these periods are defined by the period spanning the first day of month at 00:00:00 UTC until the Last day of month at 23:59:59.999 UTC

5.4.2 Grid Definition

The projection is defined as the Equal-Area Scalable Earth Grid version 2 (EASE2-Grid)

Table 9: Projection used for Level-3 thematic winter sea ice products in northern hemisphere

Property	Value
false_easting	0.0
false_northing	0.0
grid_mapping_name	lambert_azimuthal_equal_area
inverse_flattening	298.257223563
latitude_of_projection_origin	90.0
longitude_of_projection_origin	0.0
proj4_string	+proj=laea +lon_0=0 +datum=WGS84 +ellps=WGS84 +lat_0=90.0
semi_major_axis	6378137.0

Table 10: Projection used for Level-3 thematic winter sea ice products in southern hemisphere

Property	Value
false_easting	0.0
false_northing	0.0
grid_mapping_name	lambert_azimuthal_equal_area
inverse_flattening	298.257223563
latitude_of_projection_origin	-90.0
longitude_of_projection_origin	0.0
proj4_string	+proj=laea +lon_0=0 +datum=WGS84 +ellps=WGS84 +lat_0=-90.0
semi_major_axis	6378137.0

Table 11: Grid extent and spacing for Level-3 thematic winter sea ice products in both hemispheres

Property	Value
Grid Dimension	(432, 432)
Grid Spacing (km)	25.0
Grid Notation	Center Coordinates
Grid x extent in projection coordinates (km)	(-5387.5, 5387.5)
Grid y extent in projection coordinates (km)	(-5387.5, 5387.5)

5.5 Parameter Gridding

The input processing level for the gridding process are Level-2 (l2) files. The positions of all Level-2 data points in these files for the selected period are transformed to projection coordinates and subsequently associated to the index of the corresponding grid cell on the target grid. All geophysical variables of the Level-2 data are then added to parameter stacks for each grid cell.

Finally, we compute the gridded parameter geophysical p_{L3} based on the stack of Level-2 data ($p_{i,L2}$) using the 'nanmean' function of the python numpy module.

$$p_{L3} = \frac{1}{n_{L2}} \cdot \sum_{i=0}^{n_{L2}} p_{i,L2} \quad \text{if } p_{i,L2} \neq NaN$$

The following Level-2 parameters are gridded using the average method:

1. radar freeboard
2. sea ice freeboard
3. snow depth
4. snow density

The following Level-2 parameters are gridded using the median method

1. marginal ice zone flag

5.5.1 Uncertainty of Gridded Parameters

The process of averaging reduces random errors in observations, however not all error contributions in the sea-ice thickness retrieval are random (Ricker et al., 2014). Since all geophysical variables in the Level-2 data have an associated uncertainty, the Level-3 processor provides a corresponding uncertainty variable for gridded data and different strategies are in place depending on the nature of the error.

5.5.1.1 Systematic Uncertainties

The Level-3 uncertainty representation for systematic errors (e.g. snow depth) is the average of the Level-2 uncertainty and computed in the same way as the geophysical variables in the section 5.5.

5.5.1.2 Random Uncertainties

The gridded uncertainty of parameters with only random uncertainty is computed as the error of the weighted mean, since we have individual uncertainties for each value contributing to the gridded mean.

$$\hat{\sigma} = \sqrt{\sum_{n_{L2}} \frac{1}{(\sigma_{L2})^2}}^{-1}$$

This approach applies only to the radar freeboard, whose two error contributions range noise and sea surface height interpolation uncertainty are both defined as random error contributions.

5.5.1.3 Mixed Systematic and Random Uncertainties

Level-2 parameter uncertainties that based on error propagation with both random and systematic error contributions, such as those of freeboard or sea ice thickness, however, cannot easily be transferred to gridded uncertainties via gridding as this overestimates the error. The error of the weighted mean is also not an option as it essentially reduces the uncertainty to zero for grid cells with significant amounts of Level-2 data points.

We therefore re-compute the error propagation of freeboard and thickness with the stacks of all geophysical variables the uncertainties and use average ($\bar{\sigma}$) or weighed mean error ($\hat{\sigma}$) where appropriate.

This results in Level-3 uncertainty computations for freeboard:

$$\sigma_{l3,frb} = \sqrt{(\Delta r_{WP} \cdot \bar{\sigma}_{sd})^2 + (\hat{\sigma}_{rfrb})^2}$$

6 EXAMPLES

6.1 Trajectory Sea-Ice Freeboard

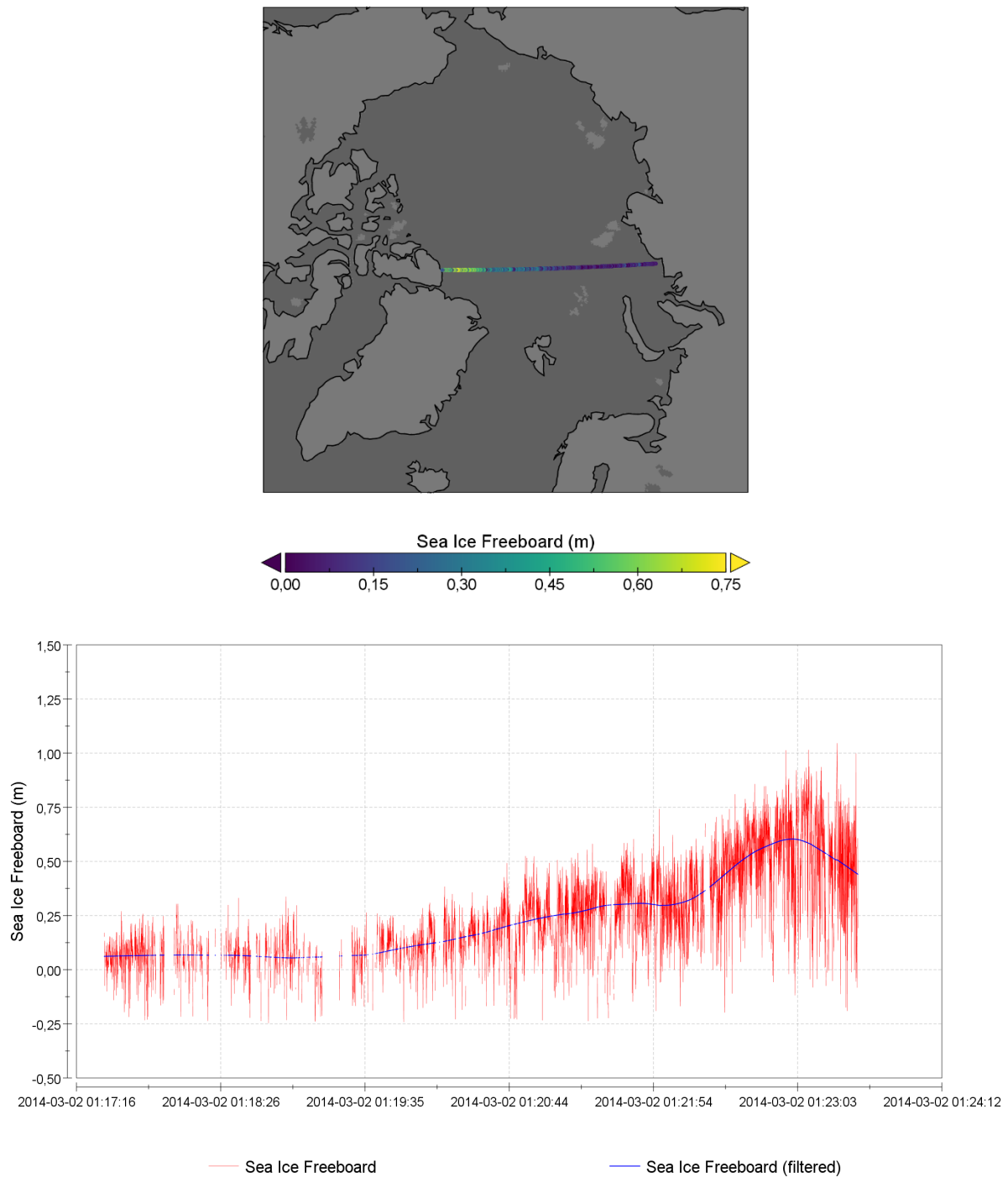


Figure 14: Sea-ice freeboard example from absolute orbit number 20658 on March 2, 2014. Upper panel: Map, lower panel: Along-track (east to west on map) of sea-ice freeboard and filtered sea ice freeboard.

6.2 Level-3 Gridded Sea Ice Freeboard

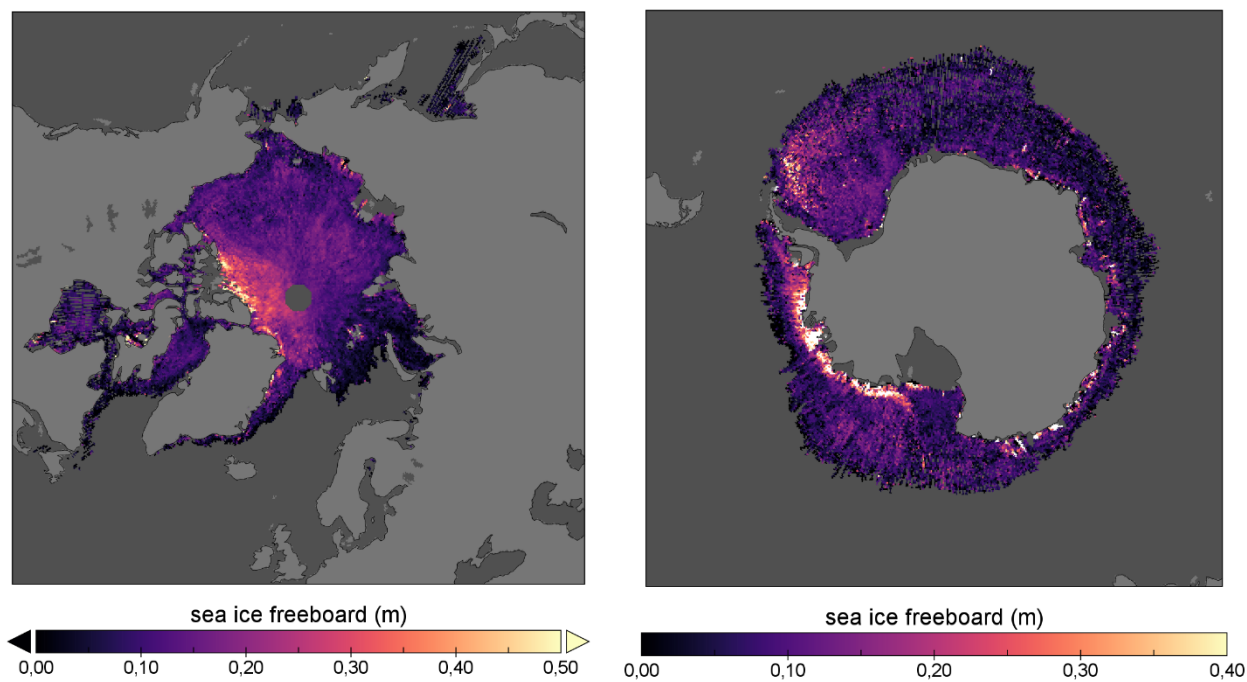


Figure 15: Examples of gridded sea ice freeboard in the northern hemisphere (left) and southern hemisphere (right)

7 KNOWN ISSUES

There are several known limitations and error contributions in the sea-ice freeboard retrieval process with radar altimeter data that affects the uncertainty of the variables in the Cryo-TEMPO thematic winter sea ice product. Most prominently is the large variability of the sea ice surface and its snow cover throughout the stages of development of sea ice that can strongly influence the return signal of a radar altimeter. The most prominent potential error contributions for sea-ice freeboard from CryoSat-2 radar altimeter data that must be noted are:

1. Snow depth on sea ice has a direct impact on the sea-ice freeboard process, but observations are not available for the full CryoSat-2 data record. Climatological data is used in the absence of direct observations and consequently, the regional, seasonal and interannual variability and change of snow depth is not fully captured. A fraction of approximately 20% of the snow depth error propagates into the sea-ice freeboard error.
2. The sea-ice freeboard retrieval assumes that radar backscatter from the snow layer has a negligible effect on the waveform shape and that the impact of snow is limited to a signal delay due to lower the radar wave propagation speed than in vacuum. Several studies however have demonstrated (Kwok 2014; Kurtz et al., 2014; Ricker et al., 2015; Nandan et al., 2017) that snow interface and volume backscatter influence retracker range under certain physical conditions. However, including this effect into the sea-ice freeboard retrieval requires the information on the properties of the snow layer, which are currently unavailable at basin scale. As a result, sea-ice freeboard may be biased high in the order of a few centimetres in periods and regions where backscatter from the snow layer is relevant.
 - a. This is especially true in the southern hemisphere where sea ice freeboards are highly likely biased high due to internal ice layers in the snow cover. The lack of wide-spread melt ponds on Antarctic sea ice allows year-around surface type classification and sea ice freeboard retrieval. The wet snow during austral summer will cause an additional bias on the freeboards.

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