

Product User Guide & Algorithm Specification

AWI CryoSat-2 Sea Ice Thickness (version 2.1)

Issued by

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Parameter & Abbreviation Index

AWI	Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research
AMSR2	Advanced Microwave Scanning Radiometer 2
C3S	Copernicus Climate Change Services
CCI	Climate Change Initiative
CDR	Climate Data Record
CET	Central European Timezone
DTU	Danish Technical University
EASE	Equal-Area Scalable Earth Grid
ELEV	Surface Elevation
ESA	European Space Agency
FRB	Freeboard
FTP	File Transfer Protocol
FYI	First-year sea ice
GCOS	Global Climate Observing System
IUP	Institute for Environmental Physics, University of Bremen
LEW	Leading Edge Width
LRM	Low Resolution Mode
MSS	Mean Sea Surface
MYI	Multi-year sea ice
NaN	Not a Number
NetCDF	Network Common Data Format
NRT	near real-time product timeliness
OCOG	Offset Centre of Gravity Retracker
OSI SAF	Ocean and Sea Ice Satellite Application Facility
PP	Pulse Peakiness
pysiral	PYthon Sea Ice Radar ALtometry toolbox
REP	reprocessed product timeliness
RFRB	Radar Freeboard
SAR	synthetic aperture radar
SARin	Interferometric synthetic aperture radar
SD	Snow Depth
SIC	Sea Ice Concentration
SIG0	Nadir Radar Backscatter Coefficient
SIRAL	Synthetic Aperture Interferometric Radar Altimeter
SIT	Sea Ice Thickness
SSA	Sea Surface (Height) Anomaly
SSH	Sea Surface Height
TAI	Temps Atomique International
TFMRA	Threshold First Maximum Retracker Algorithm
TWV	Total number of Waveforms
UTC	Coordinated Universal Time
VF	Valid Fraction
VWF	Number of Valid Waveforms
W99	Warren 99 Snow on Sea Ice Climatology

1 Introduction

1.1 Purpose of this Document

This document provides an overview of all aspects of the CryoSat-2 Arctic sea-ice thickness data product (version 2.1) generated at the Alfred Wegener Institute Helmholtz Center for Polar and Marine Research (AWI). It contains information on the

1. Primary and auxiliary data sets used in the processing
2. Description of the algorithm used deriving geophysical information along orbit segments and on space-time grids
3. Technical specifications of the product files
4. Data access
5. Known Issues of the data record

1.2 Scope of the AWI Sea-Ice Altimetry Production System

The development of a sea-ice (freeboard & thickness) product was started at the Alfred Wegener Institute (AWI) in 2014 with the goal evaluation the mass balance of Arctic sea ice and its uncertainties from CryoSat-2 sea ice altimetry. Since then, the AWI CryoSat-2 sea ice product has been the basis for climate data records (CDR) of European initiatives such as the ESA Climate Change Initiative (CCI) and the Copernicus Climate Change services (C3S) as well as a testbed for algorithm evolutions of these CDR's. It is also an input dataset for the merged CryoSat-2/SMOS sea-ice thickness dataset developed at the AWI. The algorithm development and the resulting data record have contributed to numerous scientific studies and assessments of the state of Arctic sea ice.

The AWI CryoSat-2 product is generated in the Arctic winter month of October through April in near-real time to support operational capability for analyzing the state of Arctic sea ice with minimal time delay.

⚠ An extension of the data product into the southern hemisphere as well as to other satellite altimeters (Sentinel-3A/B, AltiKA, ICESat-2) is under investigation.

1.3 Level of Commitment

A central paradigm of the AWI CryoSat-2 sea-ice thickness product is an open science approach with public and open access to data products and the underlying software. The development target is to support the FAIR principles¹ for data science.

Our intention is to develop and implement algorithm evolutions on a yearly basis. The update of the production system will occur during the summer period, when no sea-ice thickness data is available. The entire CryoSat-2 time series will be reprocessed with the new algorithm in order to have a consistent sea ice data record and the processing will resume with the new product version in October.

We are firmly committed to maintain and update the AWI sea ice altimetry production system for the near future, though no direct external funding exist for this activity.

¹ <https://www.go-fair.org/fair-principles/>

1.4 Target Requirements

The target requirements for sea ice thickness in terms of uncertainty and stability of a data record for climate research have been defined in the most recent GCOS document (GCOS report no. 154: SYSTEMATIC OBSERVATION REQUIREMENTS FOR SATELLITE-BASED DATA PRODUCTS FOR CLIMATE, 2011 update. Supplemental details to the satellite-based component of the “Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)” December 2011, ref. 18).

Table 1: GCOS Target requirements and achievable performance [D3] for remote-sensed sea ice thickness product in climate applications

Requirement	GCOS Target	Achievable Performance
Horizontal Resolution	25 km	25 km
Temporal Resolution	Monthly	Monthly
Accuracy	0.1 m	0.5 m
Stability	Unspecified	Unspecified

While the sea ice thickness product meets the GCOS target requirements for horizontal and temporal resolution, the expected product uncertainty is larger than the GCOS requirement of 10 cm. No specification is given for the stability of the sea ice thickness time series.

1.5 Further Information

1.5.1 CryoSat-2 Input Data

For all information of the CryoSat-2 mission and ESA data products please refer to the *CryoSat Product Handbook*, which is available for download at the ESA Earthnet Online. Additional information on the status of CryoSat-2 and its data products can be found on the following websites:

[ESA – Living Planet Programme – CryoSat](#)

[ESA – CryoSat-2 Wiki](#)

[UCL - CryoSat Performance and Quality Monitoring](#)

1.5.2 AWI Online Documentation and Blog

News and updates of the AWI CryoSat-2 sea ice product can be found online

[AWI – Sea Ice Radar Altimetry Wiki](#)

[AWI – Sea Ice Radar Altimetry Blog](#)

2 Production System

This section describes the production system, which consists of the software environment, its configuration and the input datasets.

2.1 Processing Environment

The processing system is based on `pysiral`, the python sea ice radar altimetry toolbox. The toolbox is developed as an open source project (<https://github.com/shendric/pysiral>). The software package and all management scripts are under revision control and run in a CentOS based-environment.

2.2 Product Timeliness

Sea ice products are generated at two timeliness versions based on the two data streams of input data from CryoSat-2:

NRT (near-real time)	+ 2 days
REP (reprocessed)	+ 33 days

Processing at AWI infrastructure is scheduled at early morning CET, which adds a few hours to the timeliness after the availability of input data at ESA servers.

NRT products are obsolete when a REP product is available for the same period.

2.3 Input Data

Input data falls in two categories: 1) primary data consisting of radar altimeter data over ice-covered ocean and 2) auxiliary data as data sets that are used for the parametrization of the sea-ice thickness retrieval algorithm.

2.3.1 Primary Altimeter Data

The primary radar altimeter dataset for the AWI sea ice product is the CryoSat-2 Level-1B data record from the ESA instrument processing facility (processor baseline C). The product files contain geolocated echo waveforms, range corrections and flags of the radar altimeter SIRAL. The altimeter data covers a narrow swath along the nadir point of the satellite orbits.

The altimeter operates in different modes² depending on surface type. Sea ice areas are covered by SAR and SARin modes and data from both modes are utilized in the AWI sea ice processor.

² <https://earth.esa.int/web/guest/-/geographical-mode-mask-7107>

Table 2: CryoSat-2 orbit and radar altimeter parameters

Data Period	Northern winter month (full)	Nov 2010 – on-going
Orbit	Repeat cycle	369 days; 30 day sub-cycle
	Altitude	717 km
	Inclination	92.00°
	Period	100 minutes
Radar Altimeter	Name	SIRAL
	Wave band	13.575 GHz (Ku-Band)
	Type	Doppler-delay (SAR) Doppler-delay interferometric (SARin)
	Footprint	0.3 km x 1.6 km (along x across track)

2.3.2 Auxiliary Parameter

Datasets that provide auxiliary parameters to the geophysical retrieval are listed below in Table 3. No distinction is made between the two timelines of CryoSat-2 data (see 2.2).

Table 3: Auxiliary sea ice parameter and their sources

Parameter	Description	Temporal Resolution	Source
Mean Sea Surface Height	DTU18: Gridded mean sea surface height from multi-sensor altimetry data	Static	DTU Space (FTP)
Sea Ice Concentration	Daily Sea Ice Concentration Analysis from OSI SAF EUMETSAT (OSI-401)	Daily	EUMETSAT OSISAF (http://www.osi-saf.org/)
Sea Ice Type	Daily Sea Ice Type Analysis from OSI SAF EUMETSAT (OSI-403)	daily	EUMETSAT OSISAF (http://www.osi-saf.org/)
Snow depth on sea ice	Merged Climatology from IUP AMSR2-based snow depth and Warren Climatology	Monthly (Static)	(see section 4.4) (FTP)

2.4 Processing Levels

The production system yields a series of data products that build on each other. For the naming of these processing levels, we adopt the following naming convention³:

Table 4: Definition of data processing levels

Level	Code	Description
Level 0	L0	Sensor raw data (not used here)
Level 1	L1A	L0 data with ancillary data (not used here)
	L1B	Calibrated L1A data at full sensor resolution
	L1C	Processed L1B data (e.g. remapping of coverage)
Level 2	L2	Geophysical variables at the same resolution and location as L1B/L1C data
	L2i	L2 data with flags and auxiliary data
	L2P	Post-processed L2i data
Level 3	L3	L2 data mapped on a space-time grid
	L3C	Observations combined from a single instrument into a space-time grid.
	L3S	Observations combined from multiple instruments into a space-time grid.
Level 4	L4	Data sets created from the analysis of lower level data that result in gridded, gap-free products.

2.5 Processing Workflow

The process to derive higher level (L2, L3) data products from the input (L1) data products is handled by a set of dedicated and self-contained software elements. These are specified in Table 5 and Figure 1. Their content is described in detail in the following sections.

Table 5: Overview of dedicated processors in the sea ice production system

Level	Description	Input	Output
Level-1 Pre-Processor	Prepares and harmonizes the L1 input data	L1B	L1C
Level 2 Processor	Retrieval of geophysical parameters (freeboard and thickness)	L1C	L2i
Level 2 PreProcessor	Daily summaries of geophysical data at full resolution (trajectory data)	L2i	L2P
Level 3 Processor	Gridded data over weekly or monthly periods (space-time grids)	L2i	L3C

³ Adapted from CCI Data Standards v2, ESA Document CCI-PRGM-EOPS-TN-13-0009

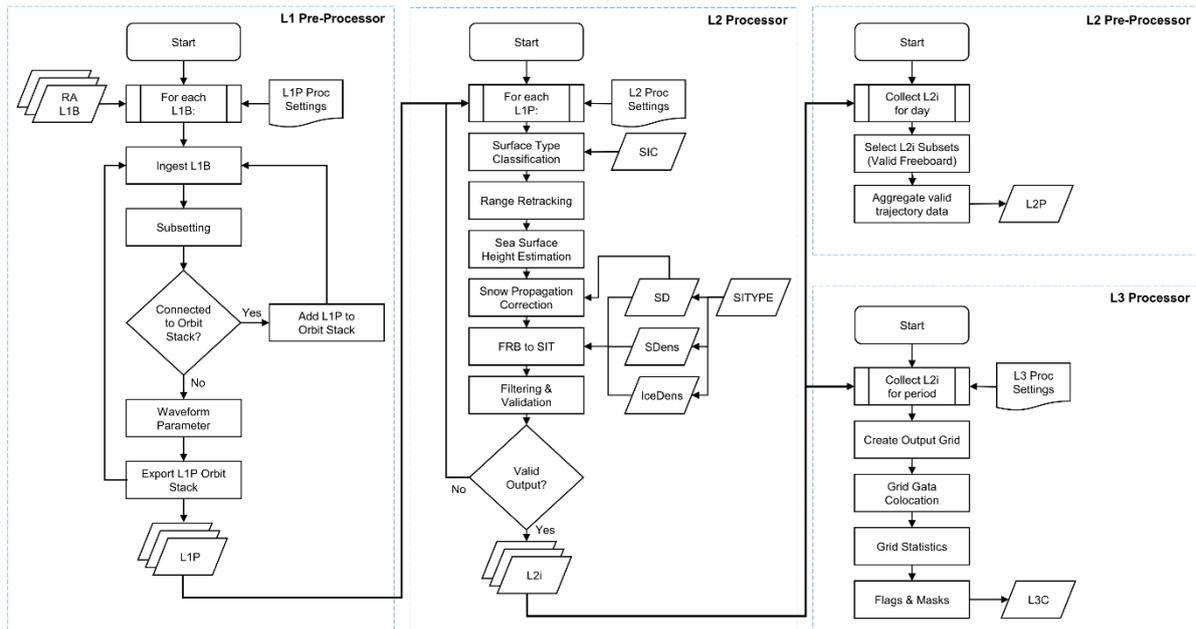


Figure 1: Workflow of the sea ice production system

3 Preparation of Primary Altimeter Data (Level-1 Pre-Processor)

The main purpose of the Level-1 Pre-Processor is to select appropriate subsets along the orbit of the satellite for the retrieval of sea ice parameters. The production system has also been designed to process data from other radar altimeter satellites than CryoSat-2, therefore one task is the generation of a unified L1C data format for generating higher level sea ice products.

The steps specific for CryoSat-2 are described below.

3.1 File format conversion

CryoSat-2 Level-1b data is delivered by ESA in form of a custom data format for ESA Earth Observation data. The variables in these files are converted to SI units and the timestamp is converted from TAI to UTC. Variables that are only available in 1Hz are interpolated to the 20Hz of the waveform data.

After the merging of relevant orbit segments (see section below), the data is saved in a NetCDF format following the pysiral L1C conventions. The content of the L1C files are several data groups:

1. Metadata
2. Time-orbit data (location and orientation of the satellite)
3. Radar waveforms
4. Geophysical range corrections
5. Surface type information
6. Waveform Classifiers

3.2 Subsetting and Merging of orbit segments

A specific characteristic of CryoSat-2 radar altimeter data is the division of orbit segments in the three different radar modes (LRM, SAR & SARin). Data from these modes are disseminated in separate product files and the pre-processor merges of individual segments where appropriate. For this purpose the L1B input files are organized as a stack of orbit segments and processed sequentially. The rationale for the merging is to enable sea-surface height estimation for a full crossing of the Arctic basin. A practical example is shown in Figure 2.

3.2.1 Orbit Subsetting

We use a southern latitude threshold of 50N as an initial regional limitation for the Arctic sea ice domain.

3.2.2 Orbit Segment Merging

Within the Arctic domain, consecutive CryoSat-2 L1B files are considered as connected when the difference between the last timestamp of the first and the earliest timestamp of the second orbit segment is not larger than 10 seconds.

Before the merging, the range window of SARin data is reduced to 256 range bins to allow merging with SAR orbit segments.

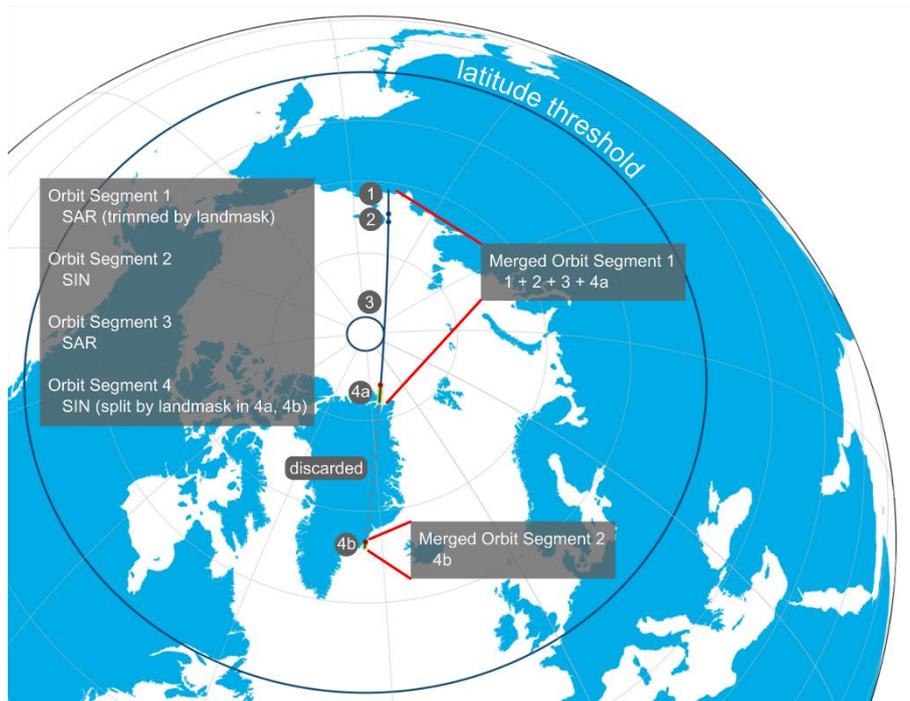


Figure 2: Exemplary merging of connected CryoSat-2 L1B product files with different radar mode by the Level-1 pre-processor

3.2.3 Data over land

Data over land or other non-ocean surface types are identified with the surface type flag in the CryoSat-2 L1B data products. Such segments are trimmed from if they occur at the edges of merged segment. If these are embedded in ocean data to both sides, they are allowed to remain if it does not affect more than 1000 data points the 20Hz samples (~ 300 km). Larger non-ocean segments are discarded and the orbit segmented is separated into two unconnected parts.

3.3 Computations of Waveform Classifiers

The Pre-processor also computes several waveform shape parameters and stores them in the L1C files for later use in the Level-2 Processor. A list of these parameters is given below:

1. Radar backscatter coefficient σ_0 in dB
2. Pulse peakiness, left & right peakiness according to Ricker et al., 2014
3. OCOG parameters (width & amplitude)
4. Leading edge width (defined as the distance between 5% to 95% TFMRA) , as well as the width of the first and second half of the leading edge (50% TFMRA)

4 Geophysical Retrieval Algorithm (Level-2 Processor)

The AWI sea-ice Level-2 processor consists of two major steps:

1. Estimation of sea-ice freeboard from CryoSat-2 radar waveforms
2. The conversion of sea-ice freeboard into sea-ice thickness with auxiliary datasets

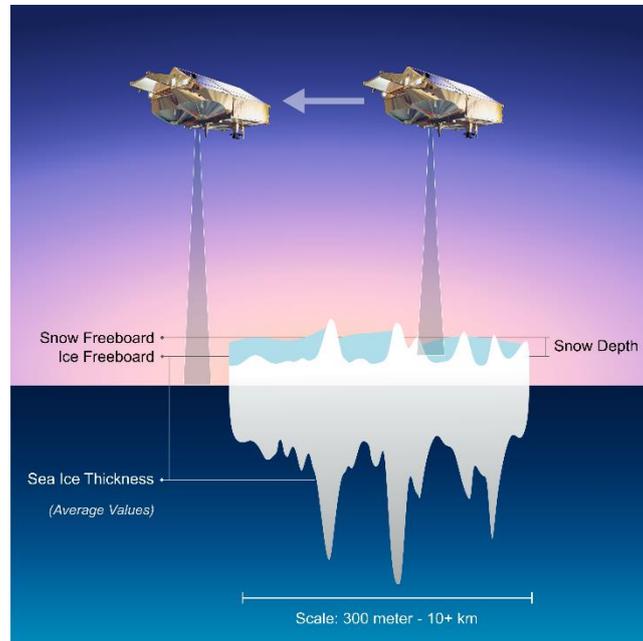


Figure 3: Principle of sea ice thickness retrieval with radar altimetry: Freeboard is derived as differential range measurements over sea ice and open water surfaces and converted into sea ice thickness based on the Archimedes Principle.

The first step requires the processing of all available CryoSat-2 Level-1b data over Arctic sea ice, while the second step consists of the interpretation of the retrieved freeboard values. Both steps require assumptions and simplifications, which are based on results of validation activities by ESA and partner organizations. These are described in the following sections. It is a major goal of this processor to estimate not only sea-ice thickness, but also the quantification of uncertainties, which arise from the quality of the level-1b and the necessary assumptions and simplifications.

4.1 Surface Type Classification

Fundamental to freeboard retrieval is the classification of surface types for each radar echo. We consider three different surface types:

1. ice surface used for freeboard and thickness retrieval
2. lead/opening between ice floes used for sea surface height estimation
3. mixed surface/unknown that are discarded from further processing

The classification is based on three parameters that describe the waveform shape and have distinct properties for waveforms over leads and ice surfaces:

1. radar backscatter coefficient (SIG0)
2. pulse peakiness (PP)
3. leading edge width (LEW)

The radar backscatter coefficient describes the reflectivity of the surface and is strongly related to the maximum power of the waveform. The pulse peakiness follows the definition of Ricker et al. (2014):

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

The leading-edge width is defined as the width in range bins along the power rise to the first maximum between 5 % and 95 % of the first-maximum peak power while using a ten-time oversampled waveform.

Thresholds for each of the three parameters have been defined for each month and each radar mode as SARin waveforms have different properties than SAR waveforms. In addition, only areas with sea ice concentrations (SIC) greater than 70% are considered a valid area for detection of leads and sea ice. The thresholds originate from Paul et al., 2018 and are summarized in tables 4 and 5.

Table 6: Waveform classification thresholds for surface type: lead

Metric	Month	CryoSat-2 SAR		CryoSat-2 SARin	
		Min	Max	Min	Max
PP	JAN	67.30		264.30	
	FEB	66.30		257.90	
	MAR	66.60		253.60	
	APR	69.90		264.60	
	OCT	76.00		291.80	
	NOV	73.80		288.80	
	DEC	68.60		272.60	
	SIG0	JAN	23.80		24.90
FEB		23.20		25.00	
MAR		23.30		24.10	
APR		23.40		24.50	
OCT		28.00		29.00	
NOV		25.80		27.40	
DEC		24.10		25.80	
LEW		JAN		0.77	
	FEB		0.78		1.11
	MAR		0.78		1.13
	APR		0.76		1.09
	OCT		0.72		1.02
	NOV		0.73		1.03
	DEC		0.76		1.07

Metric	Month	CryoSat-2 SAR		CryoSat-2 SARin	
		Min	Max	Min	Max
SIC	JAN	70		70	
	FEB	70		70	
	MAR	70		70	
	APR	70		70	
	OCT	70		70	
	NOV	70		70	
	DEC	70		70	

Table 7: Waveform classification thresholds for surface type: sea ice

Metric	Month	CryoSat-2 SAR		CryoSat-2 SIN	
		Min	Max	Min	Max
PP	JAN		30.50		99.40
	FEB		28.70		94.20
	MAR		28.10		89.90
	APR		28.50		90.00
	OCT		35.40		114.40
	NOV		34.90		113.90
	DEC		31.90		103.80
	SIG0	JAN	2.5	20.80	2.5
FEB		2.5	19.90	2.5	20.90
MAR		2.5	19.60	2.5	20.10
APR		2.5	19.00	2.5	19.10
OCT		2.5	25.70	2.5	24.30
NOV		2.5	23.20	2.5	23.70
DEC		2.5	21.10	2.5	22.00
LEW		JAN	1.02		
	FEB	1.08			1.58
	MAR	1.10			1.62
	APR	1.11			1.64
	OCT	0.91			1.44
	NOV	0.90			1.44
	DEC	0.97			1.51
	SIC	JAN	70		70
FEB		70		70	
MAR		70		70	
APR		70		70	
OCT		70		70	
NOV		70		70	
DEC		70		70	

4.2 Surface Elevation

We use an implementation of the Threshold First Maximum Retracker Algorithm (TFMRA, Ricker et al, 2014) to estimate the range to the main scattering horizon for each waveform. The sub-

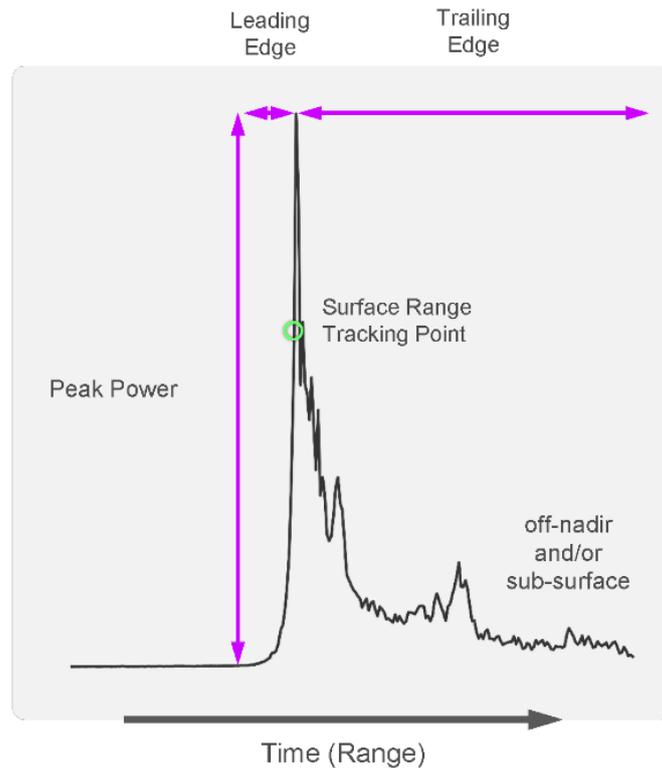


Figure 4: Example of an radar echo power as function of time with waveform shape parameters and tracking point.

waveform retracker estimates the range by computing the time where the power of the smoothed leading edge has risen to a defined percentage (Table 8) of the peak power value (see Figure 4).

Table 8: Retracker threshold parametrization for radar range retrieval over lead and ice surfaces

	Lead Waveforms	Sea Ice Waveforms
CryoSat (SAR/SIN)	50%	50%

The TFMRA returns a time that is converted into range by assuming vacuum light speed as wave propagation velocity. In reality, the wave propagation speed varies with the properties of the ionosphere and troposphere and the following corrections supplied by the primary data products are added to the range estimate:

- Ionosphere correction
- Dry troposphere correction
- Wet troposphere correction

In addition to atmospheric corrections, the range is corrected to account for sea level changes due to tides and atmospheric pressure:

- Inverse barometric correction
- Elastic ocean tide
- Long-period ocean tide
- Ocean loading tide
- Solid earth tide
- Geocentric polar tide

The source for the geophysical range corrections are CryoSat-2 L1b product finals. The final step is then the computation of surface elevation relative to the WGS84 ellipsoid by subtracting the retrieved range from the altitude of the satellite.

The uncertainty for the range retrieval and the surface elevation based on the noise of the waveform is parametrized as fixed values: 10cm.

4.3 Sea surface height

The estimation of the instantaneous sea surface height SSH along the trajectory is computed in steps:

1. Elimination of major sea level changes caused by geoid and mean dynamic topography by subtracting a mean sea surface elevation (DTU18, see 2.3.2)
2. Smoothed interpolation between elevation tie points in leads and extrapolation to the full trajectory (sea surface anomaly, SSA)
3. Uncertainty computation and filtering of SSA based on total number and distance to the next SSH tie point.

Generally written SSH is defined as:

$$ssh = mss + ssa$$

The uncertainty of the sea surface height depends on the base SSH uncertainty and the distance to the closest sea surface height tie point. The values for base SSH uncertainty is assumed to be 2 cm to include effects such as leads covered with thin ice and the maximum uncertainty is assumed as 10 cm based on investigations of the typical variation of the anomaly between the instantaneous sea surface height and mean sea surface along polar crossing orbits.

The sea surface height uncertainty is computed as

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

With d_{tp} as the distance to the next sea surface height tie point.

4.4 Snow on sea ice

The sea-ice thickness retrieval from altimeter data critically depends on the knowledge of snow (depth and density) information. In absence of a basin-scale observational data set, we utilize climatological information from the Warren et al. 1999 (W99) snow climatology of Arctic sea ice. The W99 climatology is presented as a two-dimensional quadratic fit valid for the central Arctic Basin. Earlier versions of the AWI CryoSat-2 sea ice product used W99 snow information for the ice-covered oceans in the northern hemisphere with the result of data gaps where the quadratic fit resulted in unrealistic or unphysical snow depth and density values.

4.4.1 Snow Depth

With version 2.1 we introduced a monthly snow depth and density parametrization based on merging of the W99 snow climatology and daily snow depth over first-year sea ice from AMSR2 data provided by the Institute for Environmental Physics of the University Bremen (IUP).

To merge the two data sets, we create a monthly composite of the IUP AMSR2 snow depth fields to match the monthly resolution of the W99 climatology for the month of October through April. Then we low pass filter the IUP AMSR2 snow depth composite with a Gaussian filter with the size of 8 grid cells, remove negative snow depth values and limit the upper range to 60 cm. Finally, we create a regional weight factor w that ensures a smooth transition between the inner Arctic Basin domain and the area where the AMSR2 data is used. The merged snow depth sd_{merged} is computed as:

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

See Figure 6 for visual examples of the merging steps and Figure 6 for the regional weight factor.

The uncertainty of the merged snow depth is derived in a similar fashion. We merge the uncertainty provided by the W99 climatology and the IUP AMSR2 snow depth using the regional weighting factor.

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

It is common practice to modify the W99 snow climatology by reducing its value by 50% over first-year sea ice in the central Arctic and we maintain this practice in the Level-2 processing with the ice type information for the particular orbit. However, the scaling should not be applied on the AMSR2 snow depth and use the following approach to only scale the snow depth contribution from the W99 climatology. The snow depth sd is thus

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

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

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. The uncertainty of sd is represented as the scaled uncertainty plus an uncertainty term for the scaling itself

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

The result of the merging process are significantly less data gaps outside the central Arctic Basin (see Figure 7), while the retaining the W99 information in areas potentially covered with multi-year sea ice, where AMSR2 lacks sensitivity.

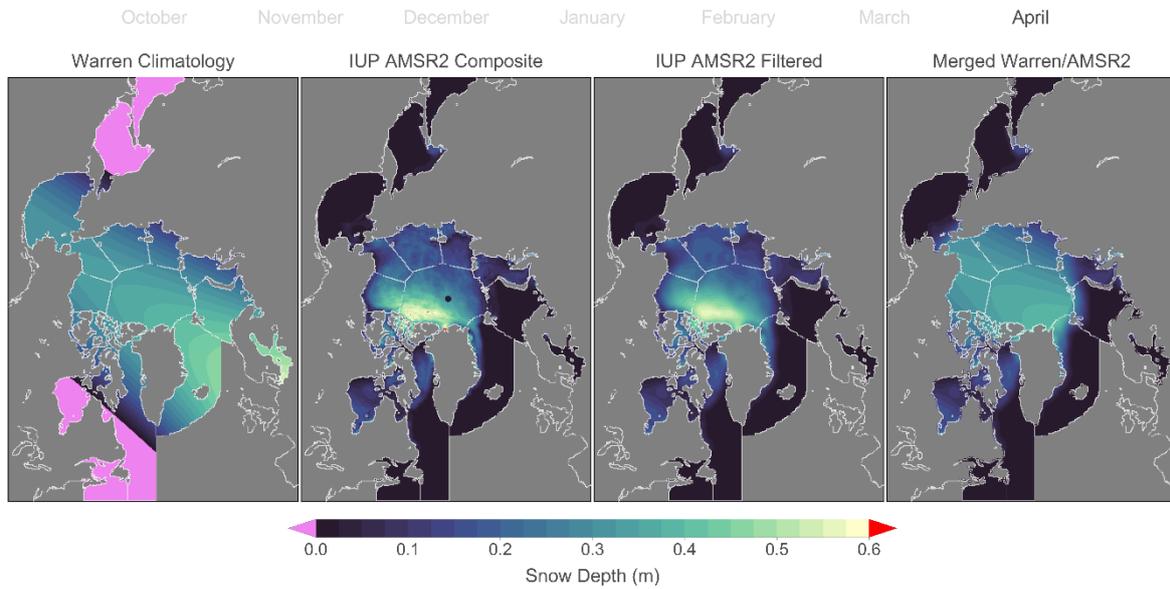


Figure 6: Steps to create a monthly merged snow depth climatology from the Warren snow climatology and monthly composites of snow depth fields derived from AMSR2 brightness temperatures by IUP Bremen. Example April, from left to right: 1) Warren snow climatology, 2) Monthly IUP snow composite from daily data, 3) Low-pass filtered IUP data and 4) merged Warren/AMSR2 with regional weighting factor

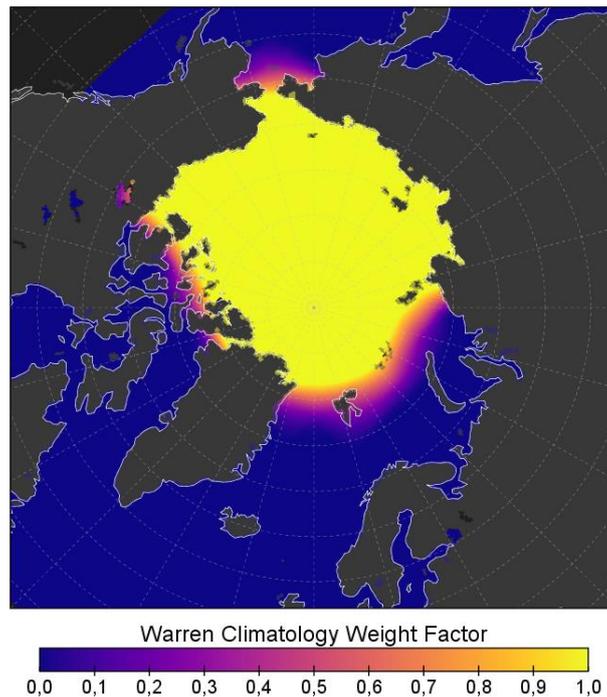


Figure 6: Regional weight factor for the Warren snow depth climatology of Arctic sea ice

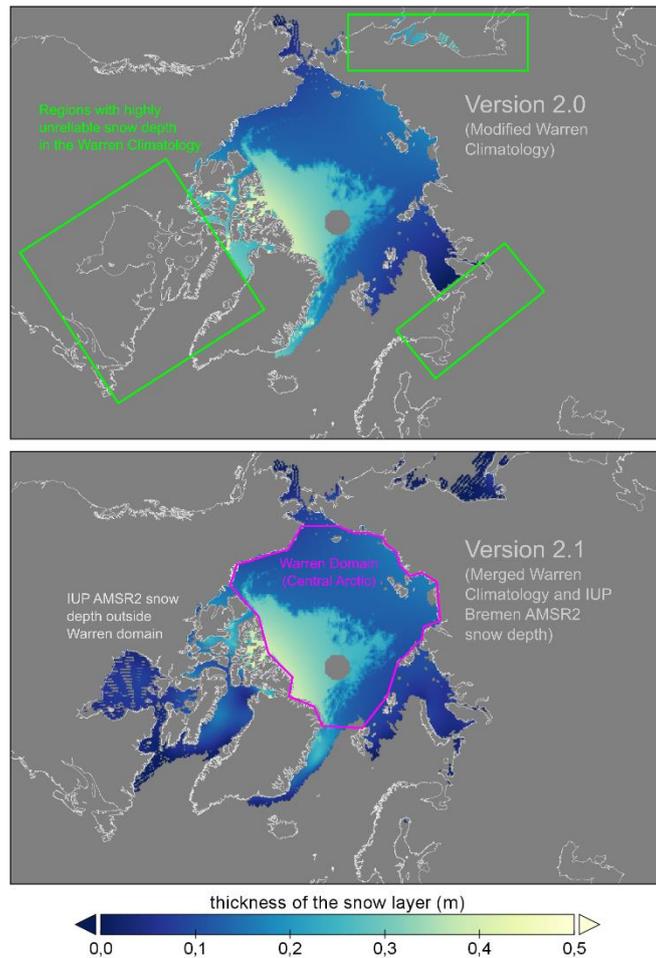


Figure 7: Comparison of W99 only (upper panel) used in v2.0 of the AWI CryoSat-2 sea ice product and merged W99 snow depth climatology (lower panel) modified by sea ice type introduced in v2.1. The merged Warren/AMSR2 snow depth climatology improves the snow depth information in areas outside the domain of the W99 climatology (central Arctic Basin)

4.4.2 Snow Density

Snow density is also provided in the monthly W99 snow climatology, but its representation as a quadratic fit also causes issues such as unrealistic/unphysical values. The AMSR2 data set does not contain density and we therefore use the W99 mean snow density and snow density uncertainty in the central Arctic Basin for all points in the northern hemisphere.

⚠ The monthly snow depth and density fields are available as public data set. (see Section 2.3.2)

4.5 Freeboard

Sea-ice freeboard is the height of the sea ice surface above the instantaneous sea surface height. Its estimation requires obtaining the range from the satellite to the snow/ice interface, since it is safe to assume that sea ice in the northern hemisphere is covered with snow in the winter month. The assumption in the AWI CryoSat-2 processing is that the influence of cold and dry snow on Ku-Band radar backscatter and thus the radar range is negligible. There are several studies shedding doubt on this assumption (see 9.1.1), however we maintain this assumption in the absence of a meaningful temporal and regional parametrizations of snow backscatter effects on radar range.

A certain impact by the snow is the slower wave propagation speed of the radar signal in the snow layer. We therefore make the distinction between the terms radar freeboard and freeboard, depending on whether any snow related correction have been applied.

4.5.1 Radar Freeboard

The initial radar-derived freeboard is then obtained by subtracting the sea surface height from the sea ice elevation, At this stage the ice elevation is based on a conversion of the two-way travel time into range r with the vacuum light speed and the altitude alt of the satellite

$$\begin{aligned} elev_{sea\ ice} &= r - alt \\ rfrb &= elev_{sea\ ice} - ssh \end{aligned}$$

4.5.2 Freeboard

The final step on the freeboard retrieval is the application of a geometric correction that accounts for the slower wave propagation speed of the radar signal in the snow layer. The correction is linear dependent on snow depth and thus implements as a fraction of snow depth and its values is based on the ration of EM wave propagation speed in snow with average density and in vacuum.

$$frb = rfrb + \Delta r_{WP}$$

with

$$\Delta r_{WP} = 0.22 \cdot sd$$

4.6 Sea Ice Density

The knowledge of sea ice density only extends to mean values for first-year (FYI) and multi-year sea ice (MYI) from a limited number of observations (Alexandrov et al., 2010). Sea ice density ρ_i is therefore a parameterization based on the sea ice type auxiliary data, while a fixed value is used for the seawater density (see Table 9).

Table 9: Densities for the sea ice freeboard to thickness conversion

	Density (kg/m ³)		Uncertainty (kg/m ³)	
Sea Water	ρ_w	1024.0	negligible	
First-year sea ice	ρ_{fyi}	916.7	σ_{ρ}^{fyi}	35.7
Multi-year sea ice	ρ_{myi}	882.0	σ_{ρ}^{myi}	23.0

$$\rho_i = \rho_{fyi} - f_{myi} \cdot (\rho_{fyi} - \rho_{myi})$$

The uncertainty of sea ice density is therefore a function of the density uncertainties of the pure ice types and the scaling process:

$$\sigma_{\rho}^i = \sigma_{\rho}^{fyi} + f_{myi}(\sigma_{\rho}^{fyi} - \sigma_{\rho}^{myi}) + \sigma_f^{myi}(\sigma_{\rho}^{fyi} - \sigma_{\rho}^{myi})$$

4.7 Sea-Ice Thickness

The estimation of sea ice thickness from freeboard is then obtained from the assumption of hydrostatic equilibrium, where the mass of ice and snow equals the mass of displaced seawater.

$$sit = \frac{sd \cdot \rho_s - frb \cdot \rho_w}{\rho_w - \rho_i}$$

The thickness uncertainty depends on all input parameters and is computed by error propagation. The density water varies not significantly and is neglected in the uncertainty budget.

$$\sigma_{sit} = \sqrt{\left(\frac{\rho_w}{\rho_w - \rho_i} \sigma_{frb}\right)^2 + \left(\frac{frb \cdot \rho_w + sd \cdot \rho_i}{\rho_w - \rho_i} \sigma_{\rho}^i\right)^2 + \left(\frac{\rho_s}{\rho_w - \rho_i} \sigma_{sd}\right)^2 + \left(\frac{sd}{\rho_w - \rho_i} \sigma_{\rho}^s\right)^2}$$

4.8 Filtering

Several filters are applied to the Level-2 data to remove erroneous data and data section with little data quality confidence:

Table 10: List of data filter for Level-2 processing of trajectory based radar altimeter data

Filter	Criterion	Action
Lead tie points	Number of detected leads < 3 in full orbit segment	Entire orbit segment is omitted
Lead tie points	No leads in marine area enclosed by land	<i>ssh</i> , <i>rfrb</i> , <i>frb</i> , <i>sit</i> set to NaN in marine area enclosed by land
Lead tie points	Distance to next lead tie point > 200 km	<i>ssh</i> , <i>rfrb</i> , <i>frb</i> , <i>sit</i> set to NaN for data points
Sea-ice Freeboard	<i>frb</i> < -0.25m or > 2.25 m	<i>frb</i> , <i>sit</i> set to NaN for data points
Sea-ice thickness	<i>sit</i> < -0.5 m or > 10.5 m	<i>sit</i> set to NaN for data points

5 Daily Orbit Summaries (Level-2 Pre-Processor)

A daily summary of Level-2 data are generated to provide easy access to CryoSat-2 sea ice altimetry products at the highest possible lateral and temporal resolution. Potential application of this data processing level are the creation of time series for local or customized areas and/or ingestion of freeboard/thickness data without prior temporal or spatial resampling.

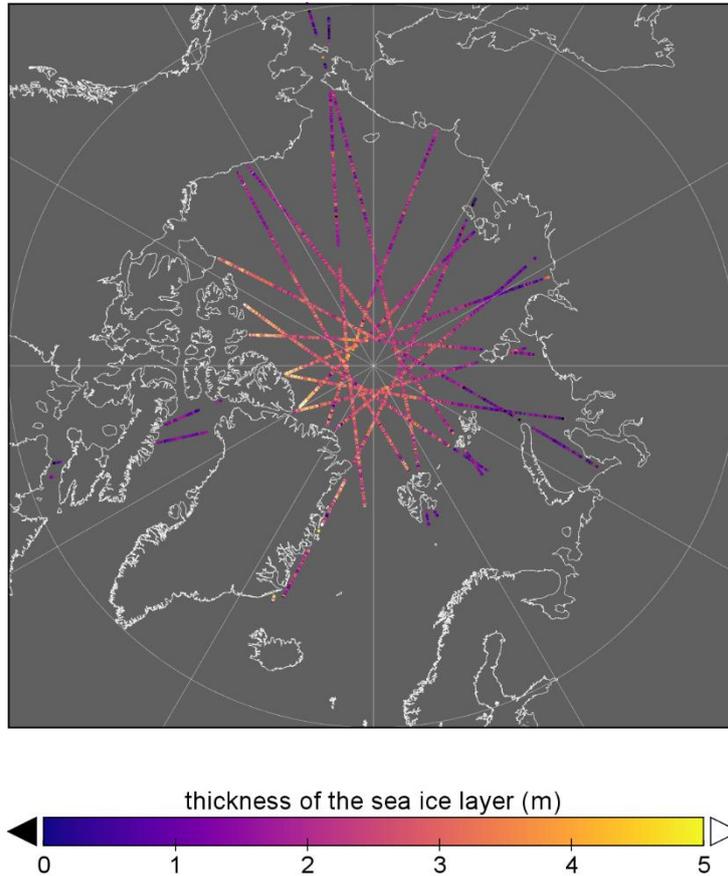


Figure 8: Exemplary data coverage of L2P sea ice thickness points within one day (April 15, 2011)

5.1 Data Coverage

The daily L2p file consist of all L2i data points between 00:00:00 – 23:59:59.999 UTC with a valid freeboard value. The geophysical variables are provided as vectors with associated geographical location and their timestamp. A description of the full content can be found in section 7.2.1.

6 Colocation on space-time grid (Level-3 Processor)

This section describes how the orbit-based Level-2 data is mapped onto spatiotemporal grids with the Level-3 processor.

6.1 Temporal Coverage

Data is gridded for weekly and monthly periods between October 1st and April 30th of each winter season. Specifically these periods are defined as follows:

Table 11: Definition of periods for gridded products

	Weekly	Monthly
Start of time coverage	Monday 00:00:00 UTC	First day of month 00:00:00 UTC
End of time coverage	Sunday 23:59:59.999 UTC	Last day of month 23:59:59.999 UTC

The two periods have a different filenaming (see 8.1), the processing is otherwise identical apart the selection of Level-2 input data. Both outputs therefore share the same processing level (Level 3 collated: L3C).

6.2 Grid Definition

The projection is defined as the Equal-Area Scalable Earth Grid version 2 (EASE2-Grid) for the northern hemisphere with a resolution of 25km. The grid resolution has been chosen to provide gapless monthly gridded products in the central Arctic Ocean.

Table 12: Projection used for Level-3 sea ice products in the 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 13: Grid extent and spacing for Level-3 sea ice products in the northern hemisphere

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)

⚠ Future product updates may be extent sea-ice thickness retrieval into the southern hemisphere as well

6.3 Parameter Gridding

The input processing level for the gridding process are Level-2 intermediate (l2i) 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.

In general, we apply no filter at this stage, as we assume that Level-2 only contains realistic results.

⚠ One exception of the no-filter approach is radar freeboard. The Level-2 notation of radar freeboard also includes measurements over leads, while the freeboard values for these points are NaN. We set radar freeboard values for leads to NaN in the Level-3 processor as otherwise the values of radar freeboard, freeboard and snow depth would not be consistent for gridded data.

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. freeboard
3. sea ice thickness
4. sea surface anomaly
5. mean sea surface
6. snow depth
7. snow density
8. sea ice density
9. sea ice type
10. sea ice concentration

6.4 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.

6.4.1 Systematic Uncertainties

The Level-3 uncertainty representation for systematic errors (e.g. snow depth, sea ice density) is the average of the Level-2 uncertainty and computed in the same way as the geophysical variables in the section 6.3.

6.4.2 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 values 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.

⚠ To maintain consistency with older versions of the data set, the average of the Level-2 radar freeboard uncertainty is also provided under the variable name `radar_freeboard_l2_uncertainty`

6.4.3 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:

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

and thickness:

$$\sigma_{l3,sit} = \sqrt{\left(\frac{\bar{\rho}_w}{\bar{\rho}_w - \bar{\rho}_i} \sigma_{l3,frb}\right)^2 + \left(\frac{frb \cdot \bar{\rho}_w + sd \cdot \bar{\rho}_i}{\bar{\rho}_w - \bar{\rho}_i} \bar{\sigma}_\rho^i\right)^2 + \left(\frac{\bar{\rho}_s}{\bar{\rho}_w - \bar{\rho}_i} \bar{\sigma}_{sd}\right)^2 + \left(\frac{sd}{\bar{\rho}_w - \bar{\rho}_i} \bar{\sigma}_\rho^s\right)^2}$$

⚠ To maintain consistency with older versions of the data set, the average of the Level-2 freeboard and thickness uncertainties are also provided under the variable names `freeboard_l2_uncertainty` and `sea_ice_thickness_l2_uncertainty`

6.5 Grid-Cell Statistics

The orbit coverage and the varying skill of the surface type classification algorithm in the Level-2 processor yields a wide range of number of samples for the gridding. The orbit coverage is increasing non-linear with latitude with a maximum at 88N. Here the point density is several magnitudes greater than at the southern sea ice limit. The number of classified waveforms is generally lower over sea ice surface with a large degree of surface-type mixing with the CryoSat-2 footprint.

These effects are documented by a set of grid-cell statistical parameters shown in Figure 9 and defined in Table 14.

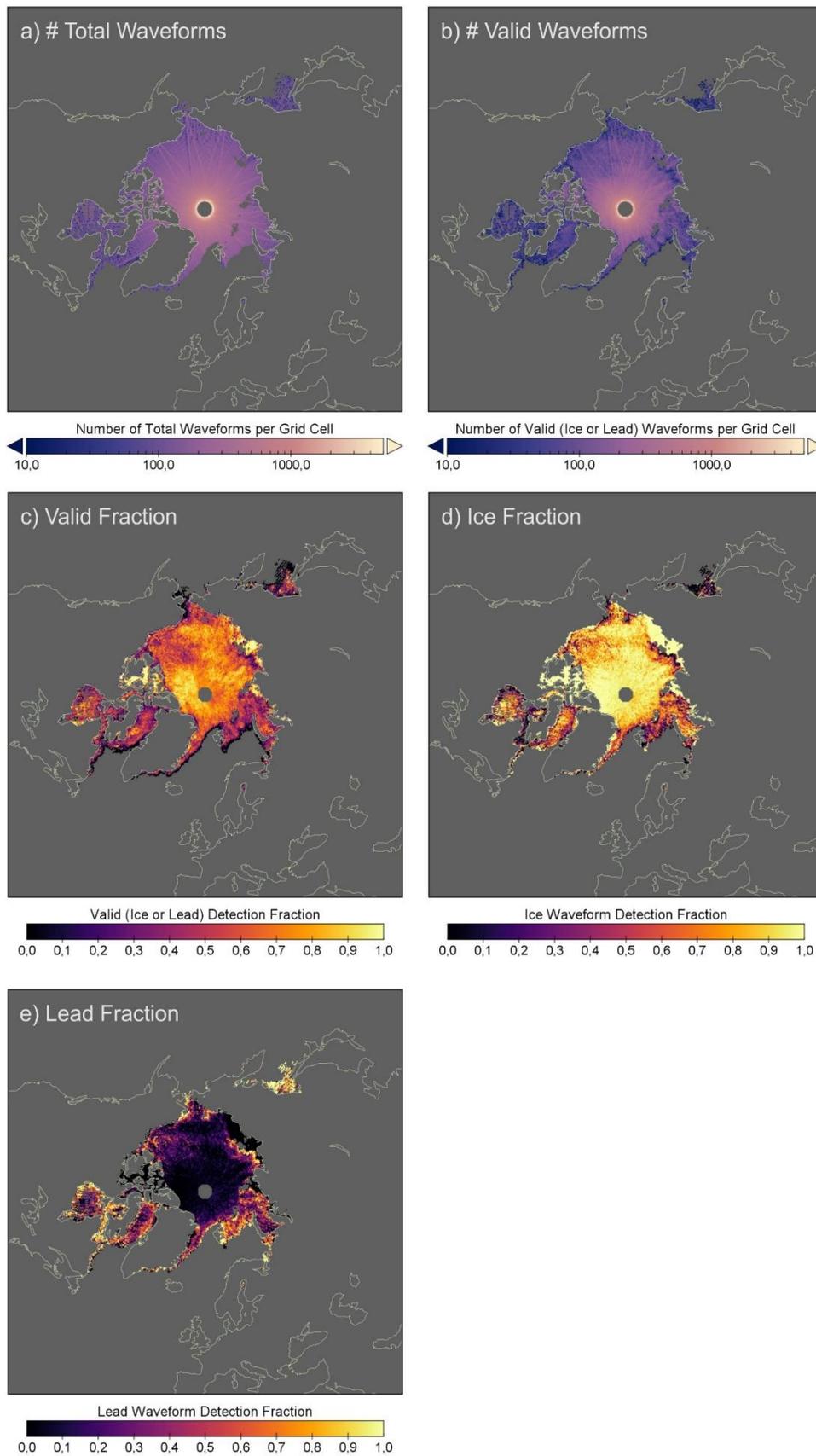


Figure 9: Example of Level-3 grid cell statistics: a) number of all waveforms per grid cell, b) number of valid waveforms classified as either ice or lead, c) fraction of ice or lead waveforms to total waveforms, d) fraction of ice detections in valid waveforms and e) number of lead detections in valid waveforms

Table 14: Definition of Level-3 grid cell statistics

Parameter	Definition	Comment
Number of total waveforms	N_{twf}	All Level-1 waveforms
Number of valid waveforms	N_{vwf}	All Level-1 waveforms that are positively classified as either ice or lead surfaces
Valid Fraction	$f_{vf} = N_{vwf}/N_{twf}$	
Ice Fraction	$f_{ice} = N_{ice}/N_{vwf}$	N_{ice} : Number of waveforms classified as ice
Lead Fraction	$f_{lead} = N_{lead}/N_{vwf}$	N_{lead} : Number of waveforms classified as leads

6.6 Flags and Masks

Level-3 products contain flags and masks to inform the user on the outcome of the retrieval and other boundary conditions for each grid cell. Figure 10 and in the subsections below give an overview of all flags in the Level-3 data products.

6.6.1 Status Flag

The status flag provides information on the availability of Level-2 input data, the sea/land mask and the success/failure of the retrieval. The flag value (Table 15) is unique for each grid cell.

Table 15: Status flag values and meaning of Level-3 status flag

Flag Value	Flag Meaning
0	no input data
1	outside sea ice concentration mask
2	latitude above orbit inclination
3	land, lake or land ice
4	sea ice thickness retrieval failed
5	sea ice thickness retrieval successful

⚠ Future product updates may be change the value of the status flag to be compliant with the convention that the flag value 0 indicated nominal retrieval

6.6.2 Quality Flag

The quality flag represents an educated guess of the performance of the sea-ice thickness retrieval based on several parameters and statistics. Other than the sea-ice thickness uncertainty, the quality flag is dependent also on data from adjacent grid cells. The conditions detailed in Table 16 are the basis for computing flag values in Table 17. The resulting quality flag for a given grid cell is always the lowest value/quality from the set of conditions.

Table 16: Conditions for quality flag values

Quality Flag	Criterion
Low	Outside the valid area of the Warren99 snow depth climatology
Low	Less than 10 Level-2 thickness data points per grid cell
Low	Negative thickness fraction > 40%
Intermediate	CryoSat-2 in SARin mode
Intermediate	Area lead fraction (the maximum lead fraction in grid cells with 75 km search radius) < 10%
Intermediate	Less than 10 Level-2 thickness data points per grid cell
Intermediate	Negative thickness fraction between 20% - 40%
Nominal	None of the above

Table 17: Quality flag values and meaning for Level-3 products

Flag Value	Flag Meaning
0	no input data
1	low quality
2	intermediate quality
3	nominal Quality

6.6.3 Radar Mode

CryoSat-2 data consists of two radar modes and their regional distribution can be traced with the radar mode mask in Level-3 products. For a given grid-cell the mask value is based on the median of the number of SAR/SARin Level-2 data points as the mode mask changes can happen within a grid cell. The mask therefore indicates which radar mode has the majority of points per grid cell and not their fractions.

Table 18 Radar mode flag values and meaning

Flag Value	Flag Meaning
0	Pulse-limited/LRM (not use)
1	SAR
2	SAR interferometric (SARin)

6.6.4 Region

Each grid-cell with sea ice coverage is associated to a certain region. The definition of the region is a variant of the NSIDC regions of the Arctic Ocean⁴. Here, the region definition for the central Arctic Ocean is identical to the NSIDC one, only the region of the Baltic Sea has been added for the AWI CryoSat-2 product.

⁴ <http://nsidc.org/arcticseaicenews/map-of-the-arctic-ocean/>

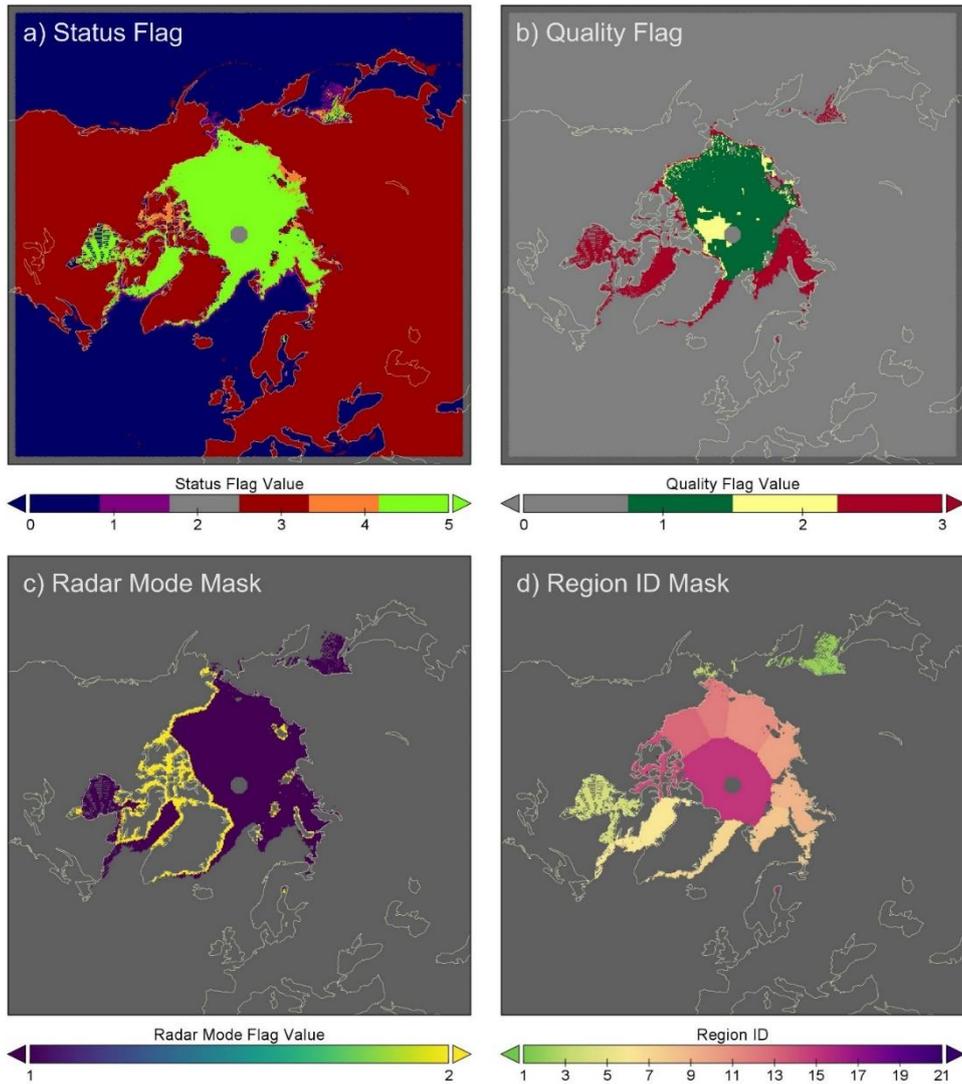


Figure 10: Examples of flags and masks in gridded Level-3 product (April 2018). a) Retrieval status flag, b) Retrieval quality flag, c) mask indicating SAR/SARin source data and d) Regions of the Arctic Ocean and Sub-arctic Seas (variant of NSIDC region mask).

Table 19: Region ID flag value and meaning

Flag Value	Flag Meaning
0	Inland sea and lakes (not used)
1	Ice-free Oceans
2	Sea of Okhotsk
3	Bering
4	Hudson Bay
5	St John
6	Baffin Bay
7	East Greenland Sea
8	Barents Sea
9	Kara Sea

Flag Value	Flag Meaning
12	Chukchi Sea
13	Beaufort Sea
14	Canadian Islands
15	Central Arctic
16	Baltic Sea
17	not used
18	not used
19	not used
20	land
21	Land outline (not used)

10	Laptev Sea
11	East Siberian Sea

7 Product Specification

This section provided the technical specifications of the output products.

7.1 File Format

All product files are provided in Network Common Data Format (NetCDF) in version 4. NetCDF is a scientific data format that is platform independent and can be parsed with any major programming language. The format also combines data and metadata, and for the latter we use the conventions for CF (Climate and Forecast) metadata.

 Please see section 8.2 for visualization of NetCDF files

7.2 Processing Levels

7.2.1 Trajectory Level-2 Pre-processed (l2p)

7.2.1.1 Filenaming

The filenames of trajectory-based products contain the following information:

awi-siral-l2p-sithick-cryosat2-<timeliness>-<hemisphere>-<period>-fv2p1.nc
where:

<timeliness>	"nrt" or "ntc"
<hemisphere>	"nh"
<period>	"YYYYMMDD"

7.2.1.2 Global Attributes

Table 20: List of global attributes and their values of L2P NetCDF files

Attribute	Value
title	"Collection of daily geophysical & auxiliary sea ice parameters from satellite radar altimetry at footprint resolution"
institution	"Alfred-Wegener-Institut Helmholtz Zentrum für Polar und Meeresforschung (AWI)"
source	"Altimetry: CryoSat-2 Level 1b baseline C (ipf1-c), Snow depth: Monthly climatology based on regional merging of Warren Climatology with 50% reduction for first-year sea ice in the central Arctic and AMSR-2 based snow depth from IUP Bremen in remaining ice-covered regions, Mean Sea Surface: DTU18 global mean sea surface, Sea ice Concentration: OSI-SAF (OSI-401-b), Sea ice type: OSI-SAF (OSI-403-c), Region code: Adapted from NSIDC region mask"

Attribute	Value
platform	"CryoSat-2"
sensor	"SIRAL"
history	"<timestamp> - Product generated with pysiral version 0.6.4.5"
references	Empty
tracking_id	"<uuid string>"
conventions	"CF-1.6"
product_version	"2.1"
processing_level	"Level-3 Collated (l3c)"
summary	"This dataset contains Level-3 monthly sea ice thickness products from satellite observations in the northern hemisphere. Level-3 data are raw observations processed to geophysical quantities, and placed onto a regular grid."
topiccategory	"Oceans Climatology Meteorology Atmosphere"
keywords	"Earth Science > Cryosphere > Sea Ice > Ice Depth/Thickness, Earth Science > Oceans > Sea Ice > Ice Depth/Thickness, Earth Science > Climate Indicators > Cryospheric Indicators > Ice Depth/Thickness, Geographic Region > Northern Hemisphere, Vertical Location > Sea Surface, Institutions > AWI > Alfred Wegener Institute for Polar and Marine Research"
id	"awi-siral-l3-cryosat2-nrt-nh_25km_ease2-<tcs>-<tce>-fv2p1"
naming_authority	"de.awi"
keywords_vocabulary	"GCMD Science Keywords"
doi	"None"
cdm_data_type	"Trajectory"
comment	"Data points only for valid freeboard retrievals"
date_created	<timestamp>
creator_name	"Alfred-Wegener-Institut Helmholtz Zentrum für Polar und Meeresforschung"
creator_type	"institution"
creator_url	"http://www.awi.de"
contributor_name	"Stefan Hendricks, Robert Ricker"
contributor_role	"PrincipalInvestigator, Author"
project	"AWI Sea Ice Radar Altimetry (SIRAL)"
publisher_name	"Alfred-Wegener-Institut Helmholtz Zentrum für Polar und Meeresforschung"
publisher_url	"www.awi.de"
publisher_email	"info@meereisportal.de"
time_coverage_start	"<tcs>" of form YYYY-MM-DDTHH:MI:SS.SSSSSS
time_coverage_end	"<tce>" of form YYYY-MM-DDTHH:MI:SS.SSSSSS
time_coverage_duration	"P1D"
time_coverage_resolution	"P1D"
standard_name_vocabulary	"CF Standard Name Table (v36, 21 September 2016)"
license	"Creative Commons Attribution 4.0 International (CC BY 4.0)"

7.2.1.3 Variables

Table 21: List of all variables (in alphabetical order) and their dimensions of L2P NetCDF files

Variable	Attributes
freeboard	double long_name = "freeboard of the sea ice layer"; standard_name = "sea_ice_freeboard"; units = "m"; coordinates = "time";
freeboard_uncertainty	float standard_name = "sea_ice_freeboard_standard_error"; long_name = "freeboard uncertainty"; units = "m"; coordinates = "time";
radar_freeboard	double long_name = "elevation of retracked point above instantaneous sea surface height"; comment = "radar freeboard is defined as the elevation based on the assumption of vacuum light speed without a snow propagation or range penetration correction"; units = "m"; coordinates = "time";
radar_freeboard_uncertainty	double coordinates = "time"; long_name = "algorithm uncertainty (error propagation) of the radar freeboard retrieval"; units = "m";
radar_mode	double coordinates = "time"; flag_meaning = "0: pulse limited (1rm), 1: sar, 2: sar interferometric"; flag_values = "0, 1, 2"; long_name = "radar mode flag"; units = "1"; valid_max = 2.0; // double valid_min = 0.0; // double
region_code	double comment = "Added flag for Baltic Sea (flag value 16)"; coordinates = "time"; flag_meaning = "0: Inland sea and lakes, 1: Ice-free Oceans, 2: Sea of Okhotsk, 3: Bering, 4: Hudson Bay, 5: St John, 6: Baffin Bay, 7: East Greenland Sea, 8 Barents Sea, 9: Kara Sea, 10: Laptev Sea, 11: East Siberian Sea, 12: Chukchi Sea, 13: Beaufort Sea, 14: Canadian Islands, 15: Central Arctic, 16: Baltic Sea, 20: land, 21 :land outline"; flag_values = "0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 20, 21"; long_name = "Region code (adapted from NSIDC region mask)"; units = "1"; valid_max = 21.0; // double valid_min = 0.0; // double

Variable	Attributes
sea_ice_density	Double standard_name = "sea_ice_density"; long_name = "density of the sea ice layer"; units = "kg m-3"; coordinates = "time";
sea_ice_density_uncertainty	double long_name = "uncertainty of the sea ice layer density"; standard_name = "sea_ice_density_standard_error"; coordinates = "time"; units = "kg m-3";
sea_ice_thickness	Double long_name = "thickness of the sea ice layer"; standard_name = "sea_ice_thickness"; units = "m"; coordinates = "time";
sea_ice_thickness_uncertainty	double long_name = "uncertainty of the sea ice layer thickness"; units = "m"; standard_name = "sea_ice_thickness_uncertainty"; coordinates = "time";
sea_ice_type	double valid_max = 1.0; // double valid_min = 0.0; // double coordinates = "time"; long_name = "fraction of multi-year ice (0: only first year ice, 1: only multi-year ice)"; standard_name = "sea_ice_classification"; units = "1";
sea_ice_type_uncertainty	double sea_ice_type_uncertainty long_name = "uncertainty of sea ice classification"; standard_name = "sea_ice_classification_standard_error"; units = "1"; coordinates = "time";
snow_density	Double long_name = "density of the snow layer"; units = "kg m-3"; coordinates = "time";
snow_density_uncertainty	Double coordinates = "time"; long_name = "uncertainty of the snow layer density"; units = "kg m-3";
snow_depth	Double coordinates = "time"; long_name = "thickness of the snow layer"; standard_name = "snow_depth"; units = "m";

Variable	Attributes
snow_depth_uncertainty	Double coordinates = "time"; long_name = "uncertainty of the snow layer thickness"; standard_name = "snow_depth standard_error"; units = "m";

Metadata Variables	Attributes
latitude	Float units = "degrees north"; long_name = "latitude of satellite nadir measurement point"; standard_name = "latitude"; coordinates = "time";
longitude	Float units = "degrees east"; long_name = "longitude of satellite nadir measurement point"; standard_name = "longitude"; coordinates = "time";
time	double units = "seconds since 1970-01-01"; long_name = "utc timestamp";

7.2.2 Space-time grid Level-3 Colated (l3c)

7.2.2.1 Filenaming

The filenames of gridded products contain the following information:

awi-siral-l3c-sithick-cryosat2-<timeliness>-<grid_id>-<period>-fv2p1.nc
where:

<timeliness>	"nrt" or "ntc"
<grid_id>	"nh_25km_ease2"
<period>	"YYYYMMDD_YYYYMMDD" (weekly product: start & end date) "YYYYMM" (monthly product)

 Start and end date for weekly products will always be Monday through Sunday. Times in UTC

7.2.2.2 Global Attributes

Table 22: List of global attributes and their values of L3C NetCDF files

Attribute	Value
title	"Monthly gridded sea-ice thickness and auxiliary parameters from satellite radar altimeter data"
institution	"Alfred-Wegener-Institut Helmholtz Zentrum für Polar und Meeresforschung (AWI)"

Attribute	Value
source	"Altimetry: CryoSat-2 Level 1b baseline C (ipf1-c), Snow depth: Monthly climatology based on regional merging of Warren Climatology with 50% reduction for first-year sea ice in the central Arctic and AMSR-2 based snow depth from IUP Bremen in remaining ice-covered regions, Mean Sea Surface: DTU18 global mean sea surface, Sea ice Concentration: OSI-SAF (OSI-401-b), Sea ice type: OSI-SAF (OSI-403-c), Region code: Adapted from NSIDC region mask"
platform	"CryoSat-2"
sensor	"SIRAL"
history	"<timestamp> - Product generated with pysiral version 0.6.4.5"
references	Empty
tracking_id	"<uuid string>"
conventions	"CF-1.6"
product_version	"2.1"
processing_level	"Level-3 Collated (l3c)"
summary	"This dataset contains Level-3 monthly sea ice thickness products from satellite observations in the northern hemisphere. Level-3 data are raw observations processed to geophysical quantities, and placed onto a regular grid."
topiccategory	"Oceans Climatology Meteorology Atmosphere"
keywords	"Earth Science > Cryosphere > Sea Ice > Ice Depth/Thickness, Earth Science > Oceans > Sea Ice > Ice Depth/Thickness, Earth Science > Climate Indicators > Cryospheric Indicators > Ice Depth/Thickness, Geographic Region > Northern Hemisphere, Vertical Location > Sea Surface, Institutions > AWI > Alfred Wegener Institute for Polar and Marine Research"
id	"awi-siral-l3-cryosat2-nrt-nh_25km_ease2-<tcs>-<tce>-fv2p1"
naming_authority	"de.awi"
keywords_vocabulary	"GCMD Science Keywords"
doi	"None"
cdm_data_type	"Grid"
comment	"Northern hemisphere sea ice thickness coverage is limited to the winter month between October and April due to negative effect of surface melt on the retrieval of freeboard."
date_created	<timestamp>
creator_name	"Alfred-Wegener-Institut Helmholtz Zentrum für Polar und Meeresforschung"
creator_type	"institution"
creator_url	"http://www.awi.de"
contributor_name	"Stefan Hendricks, Robert Ricker"
contributor_role	"PrincipalInvestigator, Author"
project	"AWI Sea Ice Radar Altimetry (SIRAL)"
publisher_name	"Alfred-Wegener-Institut Helmholtz Zentrum für Polar und Meeresforschung"
publisher_url	"www.awi.de"
publisher_email	"info@meereisportal.de"
geospatial_lat_min	"16.6239"
geospatial_lat_max	"90.0"
geospatial_lon_min	"-180.0"
geospatial_lon_max	"180.0"
geospatial_vertical_min	"0.0"
geospatial_vertical_max	"0.0"

Attribute	Value
spatial_resolution	"25km grid spacing"
geospatial_bounds_crs	"EPSG:6931"
time_coverage_start	"<tcs>" of form YYYY-MM-DDTHH:MI:SS.SSSSSS
time_coverage_end	"<tce>" of form YYYY-MM-DDTHH:MI:SS.SSSSSS
time_coverage_duration	"P1M" for monthly, "P7D" for weekly
time_coverage_resolution	"P1M" for monthly, "P7D" for weekly
standard_name_vocabulary	"CF Standard Name Table (v36, 21 September 2016)"
license	"Creative Commons Attribution 4.0 International (CC BY 4.0)"

7.2.2.3 Variables

Table 23: List of all variables (in alphabetical order) and their dimensions of L3C NetCDF files

Variable	Attributes
freeboard	double (time=1, yc=432, xc=432); long_name = "freeboard of the sea ice layer"; standard_name = "sea_ice_freeboard"; units = "m"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";
Freeboard_l2_uncertainty	float (time=1, yc=432, xc=432); standard_name = "sea_ice_freeboard_standard_error"; long_name = "algorithm uncertainty (error propagation) of the sea ice freeboard retrieval"; units = "m"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";
freeboard_uncertainty	float (time=1, yc=432, xc=432); standard_name = "sea_ice_freeboard_standard_error"; long_name = "algorithm uncertainty (error propagation) of the sea ice freeboard retrieval (computed as error of a weighted mean)"; units = "m"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";
ice_fraction	float (time=1, yc=432, xc=432); grid_mapping = "Lambert_Azimuthal_Grid"; long_name = "sea ice waveform detections per valid waveforms in grid cell"; coordinates = "time lat lon"; units = "1"; grid_mapping = "Lambert_Azimuthal_Grid";
lead_fraction	float (time=1, yc=432, xc=432); long_name = "lead waveform detections per valid waveforms in grid cell"; coordinates = "time lat lon"; grid_mapping = "Lambert_Azimuthal_Grid"; units = "1";

Variable	Attributes
mean_sea_surface	float mean_sea_surface(time=1, yc=432, xc=432); standard_name = "sea_surface_height_above_reference_ellipsoid"; coordinates = "time lat lon"; grid_mapping = "Lambert_Azimuthal_Grid"; long_name = "elevation of mean sea surface at measurement point (above WGS84 ellipsoid)"; units = "m";
n_total_waveforms	float (time=1, yc=432, xc=432); coordinates = "time lat lon"; grid_mapping = "Lambert_Azimuthal_Grid"; long_name = "number of total measurements per grid cell"; units = "1";
n_valid_waveforms	float (time=1, yc=432, xc=432); grid_mapping = "Lambert_Azimuthal_Grid"; long_name = "number of valid measurements per grid cell"; units = "1"; comment = "definition of valid: either lead or ice"; coordinates = "time lat lon";
quality_flag	byte (time=1, yc=432, xc=432); coordinates = "time lat lon"; flag_meaning = "(flag 0): no thickness data, (flag 1): nominal retrieval quality, no biases expected (flag 2): intermediate retrieval quality, bias likely (flag 3): low retrieval quality, bias expected"; grid_mapping = "Lambert_Azimuthal_Grid"; long_name = "quality indicator flag for the sea ice thickness retrieval"; standard_name = "sea_ice_thickness_status_flag"; valid_max = 3B; // byte valid_min = 0B; // byte
radar_freeboard	double (time=1, yc=432, xc=432); grid_mapping = "Lambert_Azimuthal_Grid"; long_name = "elevation of retracked point above instantaneous sea surface height (no snow range corrections)"; coordinates = "time lat lon"; units = "m"; grid_mapping = "Lambert_Azimuthal_Grid";
radar_freeboard_l2_uncertainty	double (time=1, yc=432, xc=432); coordinates = "time"; long_name = "algorithm uncertainty (error propagation) of the radar freeboard retrieval"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";
radar_freeboard_uncertainty	double (time=1, yc=432, xc=432); coordinates = "time"; long_name = "algorithm uncertainty (error propagation) of the radar freeboard retrieval"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";

Variable	Attributes
radar_mode	<pre>double (time=1, yc=432, xc=432); coordinates = "time lat lon"; :grid_mapping = "Lambert_Azimuthal_Grid"; flag_meaning = "0: pulse limited (1rm), 1: sar, 2: sar interferometric"; flag_values = "0, 1, 2"; long_name = "radar mode flag"; units = "1"; valid_max = 2.0; // double valid_min = 0.0; // double</pre>
region_code	<pre>double (time=1, yc=432, xc=432); comment = "Added flag for Baltic Sea (flag value 16)"; coordinates = "time lat lon"; :grid_mapping = "Lambert_Azimuthal_Grid"; flag_meaning = "0: Inland sea and lakes, 1: Ice-free Oceans, 2: Sea of Okhotsk, 3: Bering, 4: Hudson Bay, 5: St John, 6: Baffin Bay, 7: East Greenland Sea, 8 Barents Sea, 9: Kara Sea, 10: Laptev Sea, 11: East Siberian Sea, 12: Chukchi Sea, 13: Beaufort Sea, 14: Canadian Islands, 15: Central Arctic, 16: Baltic Sea, 20: land, 21 :land outline"; flag_values = "0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 20, 21"; long_name = "Region code (adapted from NSIDC region mask)"; units = "1"; valid_max = 21.0; // double valid_min = 0.0; // double</pre>
sea_ice_concentration	<pre>float(time=1, yc=432, xc=432); coordinates = "time lat lon"; grid_mapping = "Lambert_Azimuthal_Grid"; long_name = "sea ice concentration"; standard_name = "sea_ice_area_fraction"; units = "percent"; valid_max = 100.0f; // float valid_min = 0.0f; // float</pre>
sea_ice_density	<pre>double (time=1, yc=432, xc=432); standard_name = "sea_ice_density"; long_name = "density of the sea ice layer"; units = "kg m-3"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";</pre>
sea_ice_density_uncertainty	<pre>double (time=1, yc=432, xc=432); long_name = "uncertainty of the sea ice layer density"; standard_name = "sea_ice_density_standard_error"; coordinates = "time lat lon"; :grid_mapping = "Lambert_Azimuthal_Grid"; units = "kg m-3";</pre>

Variable	Attributes
sea_ice_thickness	double (time=1, yc=432, xc=432); long_name = "thickness of the sea ice layer"; standard_name = "sea_ice_thickness"; units = "m"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";
sea_ice_thickness_l2_uncertainty	double (time=1, yc=432, xc=432); long_name = "uncertainty of the sea ice layer thickness"; units = "m"; standard_name = "sea_ice_thickness_uncertainty"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";
sea_ice_thickness_uncertainty	double (time=1, yc=432, xc=432); long_name = "uncertainty of the sea ice layer thickness"; units = "m"; standard_name = "sea_ice_thickness_uncertainty"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";
sea_ice_type	double (time=1, yc=432, xc=432); valid_max = 1.0; // double valid_min = 0.0; // double coordinates = "time lat lon"; long_name = "fraction of multi-year ice (0: only first year ice, 1: only multi-year ice)"; standard_name = "sea_ice_classification"; :grid_mapping = "Lambert_Azimuthal_Grid"; units = "1";
sea_ice_type_uncertainty	double (time=1, yc=432, xc=432); long_name = "uncertainty of sea ice classification"; standard_name = "sea_ice_classification_standard_error"; units = "1"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";
sea_surface_anomaly	float(time=1, yc=432, xc=432); long_name = "departure of instantaneous sea surface height from mean sea surface height"; units = "m"; grid_mapping = "Lambert_Azimuthal_Grid"; standard_name = "sea_surface_height_above_mean_sea_level"; coordinates = "time lat lon";
sea_surface_anomaly_uncertainty	float (time=1, yc=432, xc=432); long_name = "uncertainty of instantaneous sea surface height"; standard_name = "sea_surface_height_above_mean_sea_level_standard_error"; coordinates = "time lat lon"; grid_mapping = "Lambert_Azimuthal_Grid"; units = "m";

Variable	Attributes
snow_density	double (time=1, yc=432, xc=432); long_name = "density of the snow layer"; units = "kg m-3"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "time lat lon";
snow_density_uncertainty	Double (time=1, yc=432, xc=432); coordinates = "time lat lon"; long_name = "uncertainty of the snow layer density"; :grid_mapping = "Lambert_Azimuthal_Grid"; units = "kg m-3";
snow_depth	Double (time=1, yc=432, xc=432); coordinates = "time lat lon"; long_name = "thickness of the snow layer"; standard_name = "snow_depth"; :grid_mapping = "Lambert_Azimuthal_Grid"; units = "m";
snow_depth_uncertainty	Double (time=1, yc=432, xc=432); coordinates = "time lat lon"; long_name = "uncertainty of the snow layer thickness"; standard_name = "snow_depth standard_error"; :grid_mapping = "Lambert_Azimuthal_Grid"; units = "m";
status_flag	byte (time=1, yc=432, xc=432); coordinates = "time lat lon"; flag_meaning = "(flag 0): no input data (flag 1): outside sea ice concentration mask (flag 2): latitude above orbit inclination (flag 3): land, lake or land ice (flag 4): sea ice thickness retrieval failed (flag 5): sea ice thickness retrieval successful"; grid_mapping = "Lambert_Azimuthal_Grid"; long_name = "status flag for the sea ice thickness retrieval"; standard_name = "sea_ice_thickness status_flag"; valid_max = 5B; // byte valid_min = 0B; // byte
valid_fraction	float (time=1, yc=432, xc=432); long_name = "fraction of valid to total waveforms"; units = "1"; coordinates = "time lat lon"; grid_mapping = "Lambert_Azimuthal_Grid"; comment = "definition of valid: either lead or ice";
lat	Float units = "degrees north"; long_name = "latitude coordinate"; standard_name = "latitude"; :grid_mapping = "Lambert_Azimuthal_Grid"; coordinates = "xc yc";

Variable	Attributes
lon	Float
	units = "degrees east";
	long_name = "longitude coordinate ";
	standard_name = "longitude";
	:grid_mapping = "Lambert_Azimuthal_Grid";
	coordinates = "xc yc";

Metadata Variables	Attributes
time	double(time=1);
	standard_name = "time";
	units = "seconds since 1970-01-01";
	long_name = "reference time of product";
	axis = "T";
	calendar = "standard";
	bounds = "time_bnds";
time_bnds	double (time=1, nv=2);
	units = "seconds since 1970-01-01";
Lambert_Azimuthal_Grid	Byte (dimensionless)
	false_easting = 0.0; // double
	false_northing = 0.0; // double
	grid_mapping_name = "lambert_azimuthal_equal_area";
	inverse_flattening = 298.257223563; // double
	latitude_of_projection_origin = 90.0; // double
	longitude_of_projection_origin = 0.0; // double
	proj4_string = "+proj=laea +lon_0=0 +datum=WGS84 +ellps=WGS84 +lat_0=90.0";
	semi_major_axis = 6378137.0; // double
xc	double xc(xc=432);
	standard_name = "projection_x_coordinate";
	long_name = "x coordinate of projection (eastings)";
	units = "km";
yc	double(yc=432);
	standard_name = "projection_y_coordinate";
	units = "km";
	long_name = "y coordinate of projection (eastings)";
lat	double (yc=432, xc=432);
	long_name = "latitude coordinate";
	standard_name = "latitude";
	units = "degrees_north";
lon	double (yc=432, xc=432);
	standard_name = "longitude";
	units = "degrees_east";
	long_name = "longitude coordinate";

8 Data Access Information

8.1 Download

CryoSat-2 data products can be accessed at the public ftp service of the Alfred Wegener Institute without prior registration.

ftp://ftp.awi.de/sea_ice/product/cryosat2/

Due to data size, data access is limited to I2p and I3c products. Products of lower processing levels are made available upon request (see section 8.3).

8.1.1 NRT products

Products based on CryoSat-2 near-real time data are not stored for the entire data record on the ftp site, but are deleted once the reprocessed data becomes available.

I2p	Link	ftp://ftp.awi.de/sea_ice/product/cryosat2/v2p1/nh/I2p_trajectory/LATEST/
	Subfolder	None
I3c (weekly)	Link	ftp://ftp.awi.de/sea_ice/product/cryosat2/v2p1/nh/I3c_grid/weekly/LATEST/
	Subfolder	None
I3m (monthly)	Link	ftp://ftp.awi.de/sea_ice/product/cryosat2/v2p1/nh/I3c_grid/monthly/LATEST/
	Subfolder	None

8.1.2 REP products

I2p	Link	ftp://ftp.awi.de/sea_ice/product/cryosat2/v2p1/nh/I2p_trajectory/
	Subfolder	<year>/<month> e.g. 2014/01/
I3c (weekly)	Link	ftp://ftp.awi.de/sea_ice/product/cryosat2/v2p1/nh/I3c_grid/weekly/
	Subfolder	<year> e.g. 2014/
I3m (monthly)	Link	ftp://ftp.awi.de/sea_ice/product/cryosat2/v2p1/nh/I3c_grid/monthly/
	Subfolder	<year> e.g. 2014/

8.2 Visualization

The NASA Panoply netCDF, HDF and GRIB data viewer (<https://www.giss.nasa.gov/tools/panoply/>) can be used as an offline viewer and is available for multiple platforms. See Figure 11 for an example.

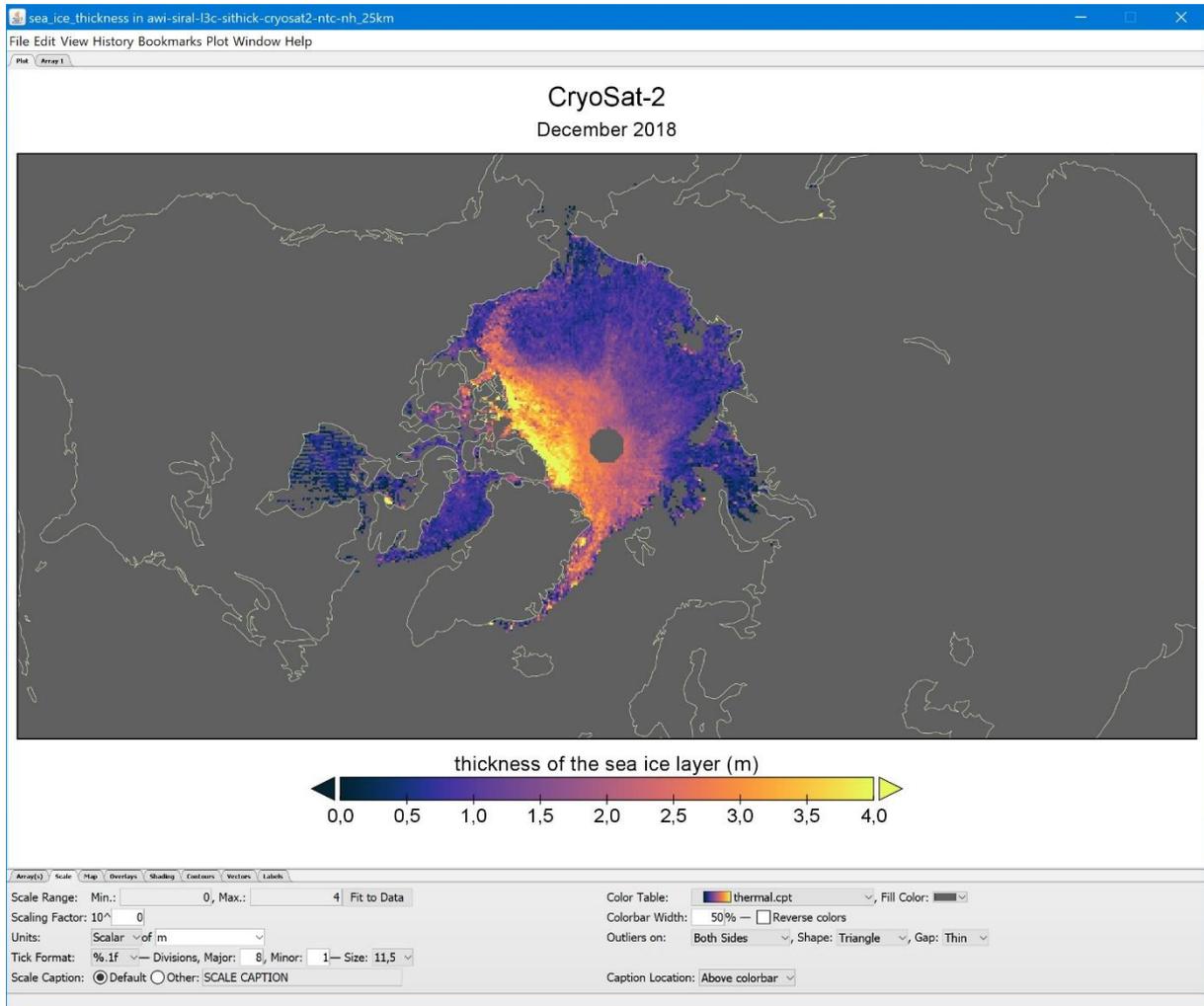


Figure 11: Visualization of a monthly gridded (I3c) sea-ice thickness field with panoply.

8.3 Point of Contact

For any inquiries please use the email (info@meereisportal.de) or web contact form of meereisportal.de (<https://www.meereisportal.de/en/contact/>).

9 Known Issues

Various components of the sea-ice thickness algorithm are an active field of research with expected improvements in the near future. Without claim of completeness or order of relevance, these fields of research include:

1. Radar ranging over sea ice surfaces with varying snow depth, stratigraphy and surface roughness
2. Estimation of instantaneous sea surface height in the marginal ice zone with low wave heights and continuity to open ocean sea surface height observations
3. Estimation of snow depth and density from re-analysis with realistic interannual and decadal variability

These topics affect various aspects of the sea-ice thickness algorithm and improvements will be implemented in future product updates upon availability. This section provides an overview of the known issues and limitations of the current algorithm and auxiliary data sets.

9.1 Freeboard

9.1.1 Snow backscatter

A key assumption in the ranging algorithm over snow covered sea ice is that the main scattering horizon is the ice/snow interface for Arctic sea ice conditions between October and April. There is however ample evidence in the scientific literature that backscatter from the snow layer can have an effect on radar ranging with Ku-Band frequencies (e.g. Kurtz et al., 2014; Kwok R., 2014; Ricker et al., 2015; Nandan et al., 2017).

Snow backscatter causes the freeboard to be biased high and thus leads to an overestimation of sea ice thickness. The ranging algorithm used for the AWI sea ice thickness product is empirical without snow depth as an input parameter, however the geometric correction used for converting the radar-derived freeboard into sea ice freeboard depends on snow depth and is an obvious candidate for including snow backscatter related range biases. However, little is known over the temporal and spatial variability of this effect on basin scale.

9.1.2 Surface Roughness

It has been shown that the magnitude of surface roughness as well as its distribution function (Landy et al. 2018) has an impact on the leading edge of the waveform. The surface roughness, respectively the leading edge width will impact the radar range and thus freeboard, especially with a fixed TFMRA threshold. An improved handling of surface roughness in the freeboard retrieval is under investigation

9.2 Sea Ice Thickness

9.2.1 Snow depth on sea ice

The current use of a static monthly snow climatology on Arctic Sea Ice (from in-situ observation and satellite data) with a resolution of 25km does not properly capture the interannual and decadal variability of snow depth and density, even with a scaling for first-year sea ice. In addition, the information does not represent variations on footprint scale. This specifically impact the thickness of young sea ice, which might have only a thin snow layer in reality, but will always be assigned the full climatological snow depth in the processing.

9.2.2 Sea-Ice Density

Similar to snow depth, the density values for sea ice also depend on a sparse set of observations and may not describe the actual density variations at the scales radar footprint resolution. The observational database originates on samples from sea ice cores, which show a significant parameter range (see e.g. Alexandrov et al. 2010).

The actual sea ice density on larger scales both depends on small-scale porosity, brine volume and the large-scale porosity of deformed & blocky sea ice. We assume that especially the variation driven by deformation are not well represented by the density samples of sea ice cores.

Airborne surveys with coincident observations of sea-ice thickness, freeboard and snow depth may provide information on sea ice density on the larger scale and its potential parametrization based on surface roughness observed by the altimeter in the near future.

10 References

- Alexandrov, V., Sandven, S., Wahlin, J., and Johannessen, O. M. (2010). The relation between sea ice thickness and freeboard in the arctic. *The Cryosphere*, 4:373–380.
- Kurtz, N. T., Galin, N., and Studinger, M.: An improved CryoSat-2 sea ice freeboard retrieval algorithm through the use of waveform fitting, *The Cryosphere*, 8, 1217-1237, <https://doi.org/10.5194/tc-8-1217-2014>, 2014.
- Kwok, R. and G. F. Cunningham (2015). Variability of Arctic sea ice thickness and volume from CryoSat-2.", *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* 373(2045).
- Landy J. C., M. Tsamados and R. K. Scharien, "A Facet-Based Numerical Model for Simulating SAR Altimeter Echoes From Heterogeneous Sea Ice Surfaces," in *IEEE Transactions on Geoscience and Remote Sensing*. doi: 10.1109/TGRS.2018.2889763
- Nandan, V., Geldsetzer, T., Yackel, J., Mahmud, M., Scharien, R., Howell, S., King J., Ricker R., Else, B. (2017). Effect of snow salinity on CryoSat-2 Arctic first-year sea ice freeboard measurements. *Geophysical Research Letters*, 44, 10,419– 10,426. <https://doi.org/10.1002/2017GL074506>
- Paul, S., Hendricks, S., Ricker, R., Kern, S., and Rinne, E.: Empirical parametrization of Envisat freeboard retrieval of Arctic and Antarctic sea ice based on CryoSat-2: progress in the ESA Climate Change Initiative, *The Cryosphere*, 12, 2437-2460, <https://doi.org/10.5194/tc-12-2437-2018>, 2018.
- Ricker, R., Hendricks, S., Helm, V. , Skourup, H. and Davidson, M. (2014): Sensitivity of CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation, *The Cryosphere*, 8 (4), pp. 1607-1622. doi: 10.5194/tc-8-1607-2014
- Ricker, R., Hendricks, S. , Perovich, D. K. , Helm, V. and Gerdes, R. (2015): Impact of snow accumulation on CryoSat-2 range retrievals over Arctic sea ice: An observational approach with buoy data, *Geophysical Research Letters*, 42 (11), pp. 4447-4455 . doi: 10.1002/2015GL064081
- Warren, S.; Rigor, I.; Untersteiner, N.; Radionov, V.; Bryazgin, N.; Aleksandrov, V. & Colony, R., Snow depth on Arctic sea ice, *Journal of Climate*, 1999, 12, 1814-1829