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Product Quality Assessment Report

Sea Ice Thickness – CryoSat-2/SMOS, Version 1.0

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History of modifications

Version	Date	Description of modification	Chapters / Sections
v1.0	10/03/2023	Initial Version	-
v1.1	27/03/2023	Document revised to account for feedback from independent review.	All

List of datasets covered by this document

Deliverable ID	Product title	Product type (CDR, ICDR, REP, OREP)	Version number	Delivery date
WP2-FDDP-2022-09	Reprocessed Northern Hemisphere Sea Ice Thickness from merged CryoSat-2/SMOS data	REP[1]	1.0	01/10/2022
WP2-ICDR-SIT-CS2SMOS-v1.0	Operationally Reprocessed Northern Hemisphere Sea Ice Thickness from merged CryoSat-2/SMOS data	OREP[1]	1.0	28/02/2023 to present

[1] The limited temporal coverage of the CS2SMOS dataset does not allow for them to be classified as CDR or ICDR categories, as is typically done for other C3S datasets. This is why the “reprocessed dataset” (REP) and “operational reprocessed dataset” (OREP) are used here instead. The OREP corresponds to the temporal extension of the REP with timely updates.

Related documents

Reference ID	Document
D1	Hendricks, S., Ricker, R., Kaleschke, L., Tian-Kunze, X. (2023) Sea Ice Thickness – CryoSat-2/SMOS Version 1.0: Algorithm Theoretical Basis Document. Copernicus Climate Change Service, Document reference: WP2-FDDP-2022-09_C3S2-Lot3_ATBD-of-v1.0-SeaIceThickness-CS2SMOS-product_v1.1.
D2	Hendricks, S. (2022) Sea Ice Thickness Version – CryoSat-2/SMOS Version 1.3: Product Quality Assurance Document. Copernicus Climate Change Service, Document ref. WP1-PDDP-2022-03_C3S2-Lot3_PQAD-of-v1.0-SeaIceThickness-CS2SMOS-product_v1.3
D3	Hendricks, S. (2023) Sea Ice Thickness Version 3.0: Product Quality Assessment Report. Copernicus Climate Change Service, Document reference: WP2-FDDP-2022-09_C3S2-Lot3_PQAR-of-v3.0-SeaIceThickness-products_v3.1.
D4	Hendricks, S. (2023) Sea Ice Thickness Version 3.0: Product Quality Assurance Document. Copernicus Climate Change Service, Document ref. WP1-PDDP-2022-03_C3S2-Lot3_PQAD-of-v3.0-SeaIceThickness-products_v3.3.

Acronyms

Acronym	Definition
AEM	Airborne Electromagnetic induction sounding
ATBD	Algorithm Theoretical Basis Document
AWI	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research
BGEP	Beaufort Gyre Exploration Project
ESA	European Space Agency
CDR	Climate Data Record
EASE2	Equal-Area Scalable Earth Grid in version 2
ECV	Essential Climate Variable
ICDR	Interim Climate Data Record
PAMARCMIP	Polar Airborne Measurements and Arctic Regional Climate Model Simulation Project
RMSE	Root Mean Square Error
SIRAL	Synthetic and interferometric radar altimeter (CryoSat-2 sensor)
SIT	Sea Ice Thickness
UTC	Coordinated Universal Time
ULS	Upward Looking Sonar

General definitions

Uncertainty and Precision

Fundamental properties of a validation exercise are the uncertainty and precision (Figure 1).

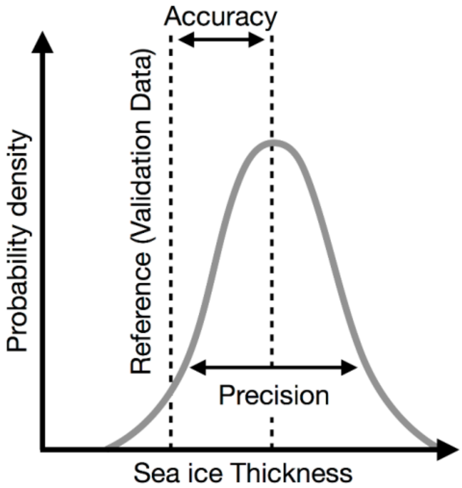

Figure 1: Schematic probability density distribution of satellite-derived sea ice thickness measurements to demonstrate the goal of the validation exercise. Accuracy is determined by the root mean square error between the satellite data and a validation data set. Precision is determined at satellite crossovers with a time delay of only several hours.

Uncertainty Describes how close the sea ice thickness value in the product files is to reference observations of a validation data set. In this validation exercise, the uncertainty is defined as root mean square error (RMSE) between the satellite data and validation data.

Precision Describes the agreement of repeat measurements of the same variable. This parameter is assessed in an area near cross-over points with a short time delay of only a few hours between different orbits of the radar altimeter data. The rationale here is that within a few hours the effect of sea ice drift and ice thickness change can be neglected and that sea ice thickness differences between the crossing orbits can be attributed to the precision of the measurement only.

Data Processing Levels

The concept of data processing levels[2] is a common way in satellite remote sensing to designate different data products. Processing levels range from Level-0 (unprocessed sensor raw data) to Level-4 (analysed and potentially gap filled geophysical parameters). The product assessment of the SIT CDR uses two specific data processing levels:

L3C	(Level-3 collated) L3C product files contain sea ice thickness data on a spatio-temporal grid. The C3S SIT CDR uses monthly periods with data from only a single radar altimeter platform.
L4	(Level-3) Data sets created from the analysis of lower level data that result in gridded, gap-free products.

ECV requirements

An essential climate variable (ECV) is a variable, or group of variables that critically contributes to the characterization of the Earth Climate System (WMO, 2022). Requirements for an ECV product is expressed by 5 criteria:

Spatial Resolution	Horizontal and vertical (if needed).
Temporal resolution (or frequency)	The frequency of observations e.g. hourly, daily or annual.
Measurement Uncertainty	The parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand. It includes all contributions to the uncertainty, expressed in units of 2 standard deviations, unless stated otherwise.
Stability	The change in bias over time. Stability is quoted per decade.
Timeliness	The time expectation for accessibility and availability of data.

For each criterion, 3 values are defined that describe the maturity of an ECV product:

Goal	an ideal requirement above which further improvements are not necessary.
Breakthrough	an intermediate level between threshold and goal which, if achieved, would result in a significant improvement for the targeted application. The breakthrough value may also indicate the level at which specified uses within climate monitoring become possible. It may be appropriate to have different breakthrough values for different uses.
Threshold	the minimum requirement to be met to ensure that data are useful.

[2] https://www.earthdata.nasa.gov/engage/open-data-services-and-software/data-information-policy/data-levels [last accessed 5th December, 2022]

Table of Contents

Scope of the document

This document provides the results from the product assessment based on the Product Quality Assurance Document [D2]. This document is intended to be public, in addition to being shared with the C3S Evaluation and Quality Control team. The document summarizes the validation exercise of version 1.0 of the sea ice thickness (SIT) CryoSat-2/SMOS data record. It contains a brief overview description of the methodology, which is described in detail in the Product Quality Assurance Document [D2], before presenting the results of the validation exercise.

Executive summary

The product quality assessment of the CryoSat-2/SMOS SIT is based on comparing gridded SIT data to validation data. The validation methodology is intentionally similar to the methodology used for the SIT CDR/ICDR ([D3], [D4]), which provides sea ice thickness information from a different approach and for a longer period.

The data base for sea ice thickness validation is very limited. It consists of airborne data with intermediate geographic coverage but poor temporal coverage, or mooring data with excellent temporal coverage but poor geographic coverage. Most of the validation data set does not measure sea ice thickness directly, but needs to be converted using auxiliary data from the SIT CDR retrieval algorithm (See [D3] and [D4]).

The main findings of the product quality assessment are:

1. The uncertainty of CryoSat-2/SMOS data (daily temporal resolution and at a spatial resolution of 25 km), based on the root mean square error between validation and satellite data, is 0.30 m.
2. The mean bias of CryoSat-2/SMOS data is -0.10 m.
3. The results are biased towards upward looking sonar (ULS) based draft measurements of the Beaufort Gyre Exploration Project (BGEP), which provides 92% of the validation data. The remain 8% originate from airborne data. Airborne data show higher uncertainty and bias, but also represent thicker sea ice than the ULS data.
4. A linear fit of the differences between CryoSat-2/SMOS and validation SIT may indicate a minor bias drift of +0.02 m per year, with earlier CryoSat-2/SMOS data potentially too thin. The linear fit however is a poor representation of the inter- and intra seasonal variability.
5. The uncertainty variable in the CryoSat-2/SMOS product files considerably underestimates the uncertainties found in the validation exercise.

1. Product validation methodology

A detailed description of the validation data sets and the validation methodology is given in the Product Quality Assurance Document [D2]. The methodology follows the approach for the product validation of the Sea Ice Thickness CDR/ICDR ([D3],[D4]) whenever possible.

1.1 Validated Products

Table 1 provides an overview of the validated products. The Sea Ice Thickness data record from CryoSat-2/SMOS data contains gridded SIT based on an optimal interpolation of gridded SIT from CryoSat-2 and SMOS. The temporal resolution of the products is daily, but each product file consists of input data from 7 days. The date in the filename indicated the date at the centre of the 7-day period.

Table 1: Product files that are subject to validation in this document. The acronyms YYYY, MM and DD refer to year, month and day respectively.

Product Description	ID
Northern Hemisphere Sea Ice Thickness from merged CryoSat-2/SMOS data Version 1.0	ice_thickness_nh_ease2-250_cs2smos-v1p0_YYYYMMDD.nc

1.2 Overview of the Validation Methodology

1.2.1 Sea Ice Thickness Validation

External reference data is used to assess the bias and uncertainty for SIT data with the spatial (25km) and temporal (1 day) resolution of the data record. The assessment uses the convention that external reference data only matching the reference date of the CryoSat-2/SMOS data product, is used for the comparison.

A selection criterion for the SIT validation is that the reference data contains information on the thickness of the sea-ice layer and not only its freeboard. Suitable candidates are sea-ice draft observations from upward looking sonars (ULS) of the Beaufort Gyre Exploration Project (BGEP) and total ice thickness observations from airborne electromagnetic induction sounding (AEM). Both reference datasets need to be converted into sea-ice thickness, using information from the SIT CDR [D3]. We also include data from the combination of AEM and snow radar (Jutila et al., 2021a) data, acquired during the IceBird aircraft campaign series. These data result in a reference data set of true sea-ice thickness (Jutila et al., 2021b) that has become available in the recent years.

The reference data is gridded to the same grid and period as the CDR, and is directly compared to the gridded sea-ice thickness information of the CDR. The following metrics are computed:

1. Number of grid cell pairs (Num).
2. Mean total difference between satellite and reference SIT data computed as satellite minus reference (Bias).
3. The Root Mean Square Error (RMSE) between satellite and reference data.
4. The Pearson correlation coefficient (R).
5. The Slope and Intercept of a linear regression of the satellite and reference difference.

The primary assessment metrics are (i) the bias as the mean total difference, and (ii) the RMSE as a measure of the SIT uncertainty at a 25km level. The available reference data covers the major fraction of the CryoSat-2/SMOS data record period, noting that spatially, the reference data are mostly located in the western seas of the Arctic Ocean (**Figure 2**).

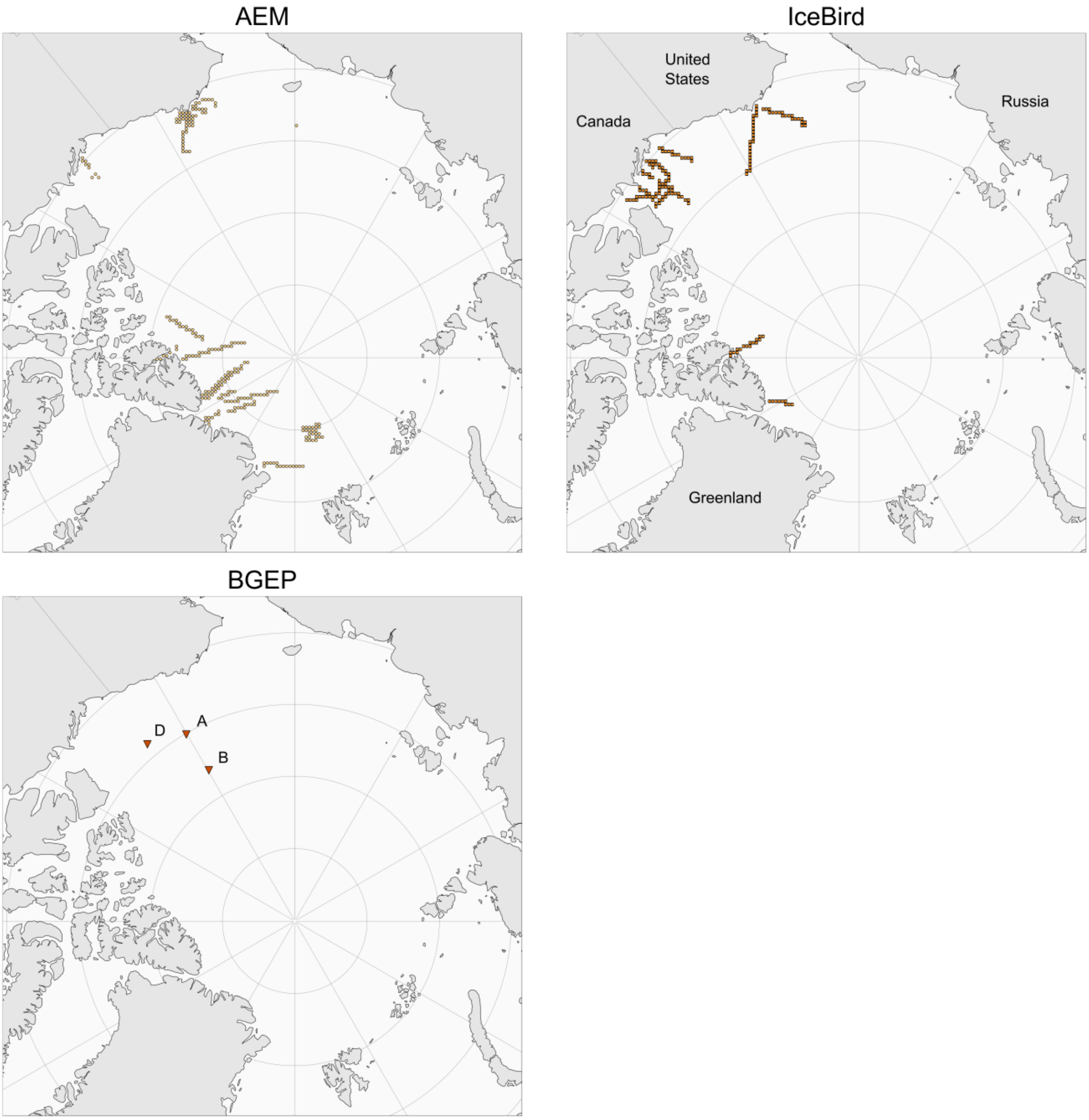

Figure 2: Location validation datasets used for sea ice thickness validation of the CryoSat-2/SMOS sea ice thickness data record. Airborne data is shown in the top row with AEM survey tracks in the upper left panel and IceBird survey tracks in the upper right panel. BGEP sites are shown using orange triangles in the lower left panel.

1.2.2 Analysis of Data Record Stability

The CryoSat-2/SMOS SIT data record starts in 2010, and is considerably shorter than the SIT CDR/ICDR which starts in 2002. Nevertheless, a drift in the stability might have occurred in the 11-year period from 2010 to 2021.

A test for data record stability therefore evaluates if the mean difference between satellite and reference sea ice thickness changes as a function of time. In this test, all available validation data is binned into daily periods and a mean difference is computed and evaluated using a linear regression analysis. The target is the absence of a slope in the linear regression, with slope absence being indicative of a stable SIT bias over time.

2. Validation results

2.1 Sea Ice Thickness Validation

The results of the satellite SIT comparison against reference data is summarized in Table 2 as well as Figure 3 showing all combinations of validation data sources.

Table 2: Results of the SIT comparison between the CryoSat-2/SMOS data record and the different reference data sources (BGEP, AEM & IceBird). The table includes the resulting statistics from the different reference source analyses, as well those for the combined reference data analysis (All).

Reference	Num	Bias (m)	RMSE (m)	R	Slope	Intercept
BGEP	5367	-0.09	0.27	0.73	0.51	0.52
AEM	295	-0.21	0.74	0.54	0.61	0.87
IceBird	162	-0.25	0.59	0.61	0.61	0.62
All	5827	-0.10	0.30	0.77	0.62	0.41

2.1.1 Sea Ice Thickness Uncertainty

The metric for sea ice thickness uncertainty is the root mean square error (RMSE) between satellite validation data.

The results vary depending on the source of validation data. The BGEP ULS data provides the majority (92%) of data points for the validation exercise, due to continuous data coverages for all days in the CryoSat-2/SMOS data record up to April 2021. AEM contributes 5% and IceBird data 3% respectively. It is also noticeable that BGEP ULS data mostly contains thinner sea ice, while airborne data sets are often collected in the thicker sea ice areas (Figure 2).

The uncertainty estimates (RMSE) derived from AEM (0.74 m) and IceBird (0.59 m) are both twice as large as from BGEP data (0.27 m) (Table 2). The difference in temporal and spatial coverage is likely to contribute to this observed deviation, noting that systematic biases between the validation data sources cannot be ruled out.

The validation uncertainty for CryoSat-2/SMOS data is defined as the RMSE of all validation data sources, and amounts to 0.30 m.

2.1.2 Aggregated Sea Ice Thickness Error

The bias, or aggregated SIT error, based on all validation data sources amounts to -0.10 m for CryoSat-2/SMOS data. But similar to the uncertainty case (Section 2.1.1), the results vary between BGEP ULS and the airborne data sets. Both AEM and IceBird show higher biases, but these data sets also cover thicker sea ice than the BGEP data.

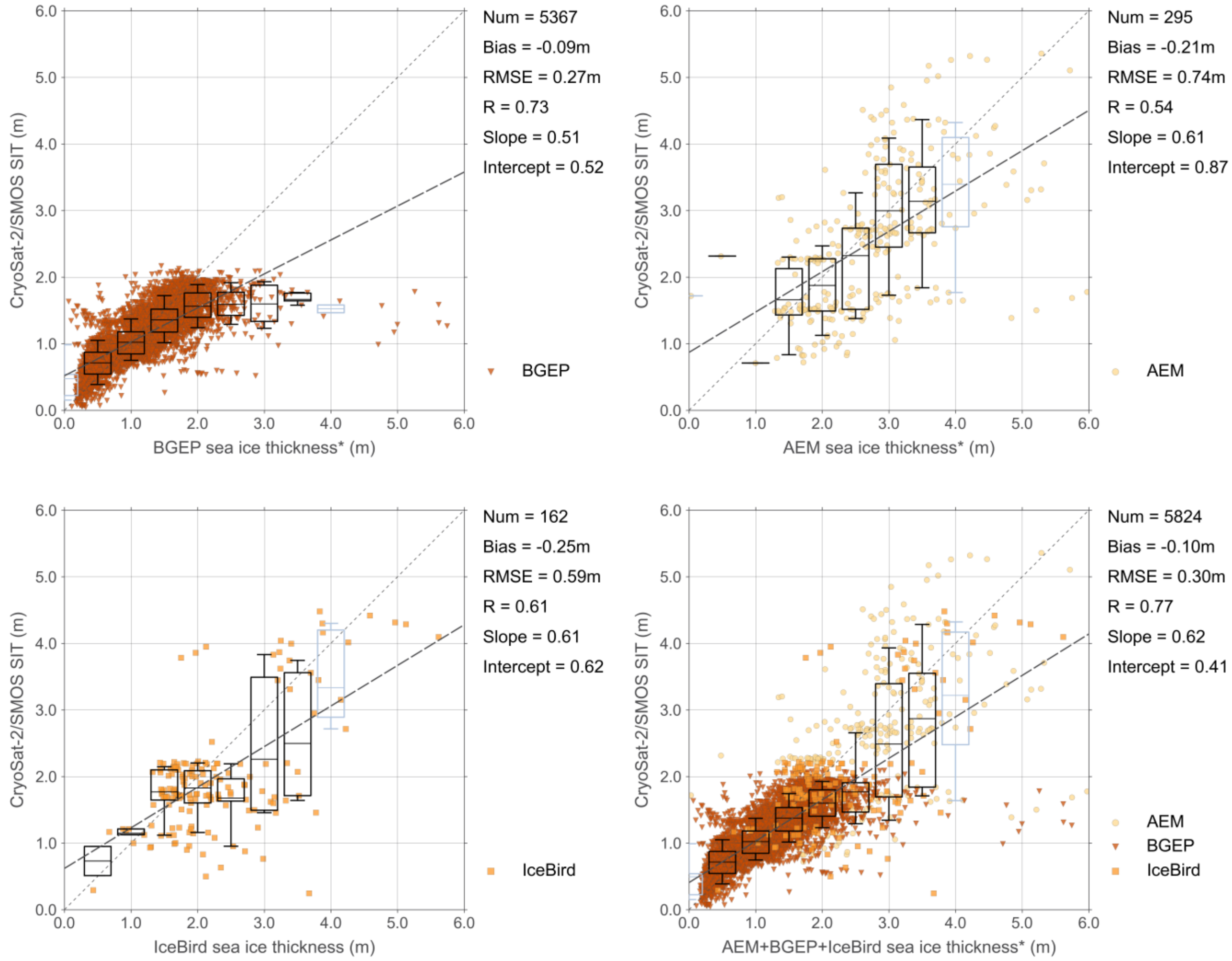

Figure 3: Comparison of satellite SIT (CryoSat-2/SMOS) with reference SIT data (BGEP: upper left, AEM: upper right, IceBird: lower left, All: lower right). Reference SIT that has been converted from another geophysical parameter (sea-ice draft, total thickness) is marked with a "*" in the axis label. Boxplots indicate difference statistics (mean, interquartile and interdecile range) within 50cm binned segments.

2.1.3 Representativeness of Sea Ice Thickness Classes

Linear fits for individual validation data sources, as well as for the sum of all validation data sources, uniformly result in a slope of < 1 (Table 2, Figure 3). This indicate there is an underestimation of thicker sea ice by the CryoSat-2/SMOS data record.

This is especially apparent in the comparison between BGEP and CryoSat-2/SMOS in Figure 3, with almost no SIT larger than 2 m in the CryoSat-2/SMOS. A potential explanation is the filter window of 250 km for the optimal interpolation [D1]. The BGEP moorings are located in the Beaufort Gyre with variable sea ice conditions, e.g. thicker multi-year sea ice with young and thin first year sea ice in between. The BGEP data is able to measure the thicker sea ice of individual floes. However, the optimal interpolation has a smearing effect that cannot properly represent small areas of thick sea ice. Larger regions of SIT > 3.0 m sensed by the airborne data are much better reproduced by CryoSat-2/SMOS, which indicated that there is no specific SIT limit, rather a limit of spatial resolution.

2.1.4 Summary and Assessment

Results from the CryoSat-2/SMOS validation are comparable to the validation of the CryoSat-2 data period in the SIT CDR [D3]. However, the daily temporal resolution of CryoSat-2/SMOS results in a significantly larger bias towards the daily BGEP mooring data in the validation. The mooring data show a better agreement with the satellite data, which results in an overall better validation metrics for the CryoSat-2/SMOS data record compared to the SIT CDR.

2.2 Analysis of Data Record Stability

2.2.1 Validation Trend Analysis

The result of the validation exercise (difference between satellite-derived and reference-derived SIT), visualized as a function of time with daily resolution is shown in Figure 4. A linear regression analysis shows a trend of 0.02m per year, but with a very low coefficient of determination of only 0.04. This means, a linear trend does not describe the satellite/validation data differences very well.

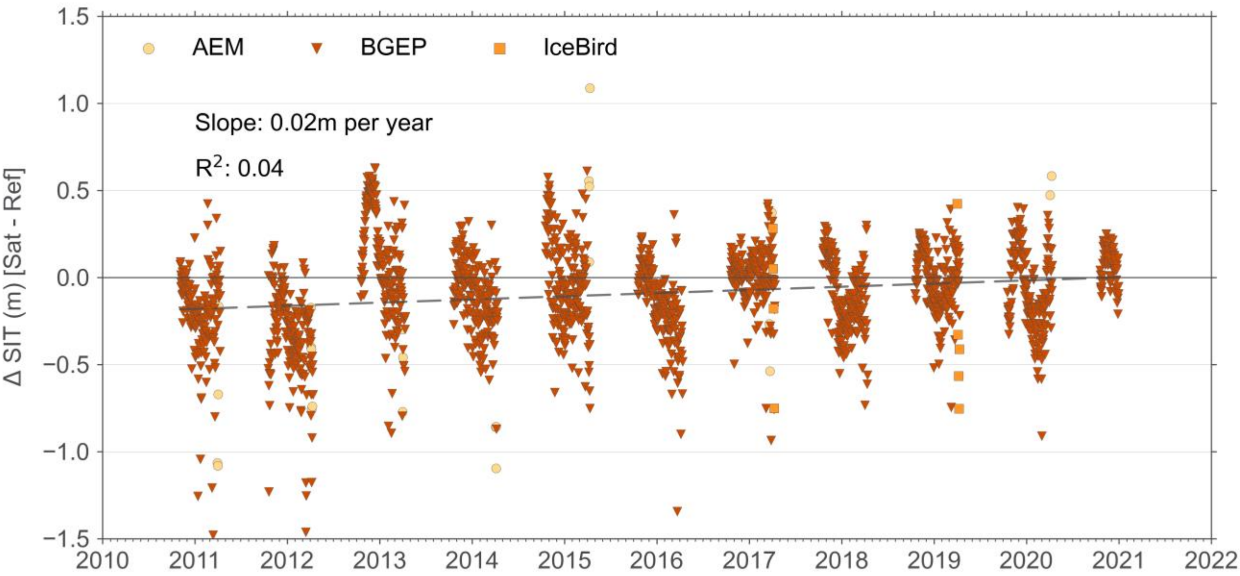

Figure 4: Stability of the CS2SMOS SIT v1.0 data record expressed as average difference between SIT and the three different types of reference data, visualised as a function of time.

The validation differences vary between, and within the 11 winter seasons in the CryoSat-2/SMOS data record. A visual inspection only indicates a minor change during summer of 2012. Before this summer, SIT differences between a CryoSat-2/SMOS and validation data seems to be more negative, while they are closer to 0 in the period after 2012.

It should be noted here that this analysis is dominated by the BGEP ULS data acquired in the Beaufort Sea. The validity of these conclusions for the full Arctic sea ice cover is doubtful.

3. Application(s) specific assessments

3.1 Sea Ice Thickness Trend Analysis

The CryoSat-2/SMOS data record is likely to be considered too short to estimate sea ice thickness trends for climate time scales. Due to the lack of L-Band radiometer data before 2010, there is also no possibility to baseline SIT information before 2010 that is consistent with the CryoSat-2/SMOS data record.

3.2 Realistic Product Uncertainty

The uncertainty parameter in CryoSat-2/SMOS product files is based on the uncertainty parameter of the optimal interpolation, which in turn depends on the uncertainty of the input CryoSat-2 and SMOS data [D1]. The magnitude is expected to roughly match the uncertainty derived from the validation exercise.

To test this, SIT estimated from the validation data, and SIT uncertainty from the CryoSat-2/SMOS data record are grouped in thickness classes with a size of 1 m (based on the validation data estimate). For each class, the SIT uncertainty from the SIT CDR product files is averaged, and the validation uncertainty is estimated from the root mean square error of all grid cells in the SIT CDR with validation data coverage. The RMSE is only computed if more than 10 such grid cell exists in a thickness category. The result is shown in Figure 5.

The results show clearly that the uncertainty parameter in the CryoSat-2/SMOS product is too small, even when a potential uncertainty overestimation in the validation exercise due to uncertainty of the validation data itself is considered. An improved CryoSat-2/SMOS product uncertainty will be the target of product developments in the next releases.

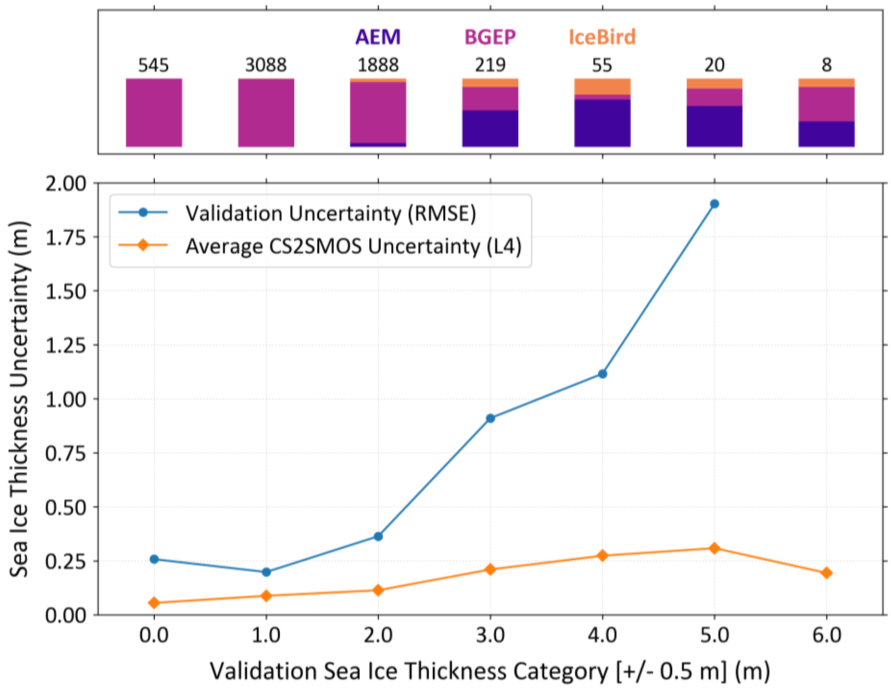

Figure 5: Intercomparing average sea ice thickness uncertainty estimate in CryoSat-2/SMOS product files, with uncertainty based on validation data. Validation data uncertainty is computed as root mean square error (RMSE) between satellite and validation data in sea ice thickness categories, with a spacing of 1 meter (based validation data). Validation uncertainty is only estimated if there are more than 10 grid cells in each thickness category. For both Envisat and Cryosat-2 results, the top panel indicates the composition of validation data sources, and total number of grid cells per thickness category.

4. Compliance with user requirements

The Global Climate Observing System (GCOS) has updated the requirements for sea ice thickness as part of the sea ice ECV in 2022 (WMO, 2022) based on a reference document (Lavergne et al, 2022).

Instead of a single set of requirements for spatial and temporal resolution, as well as uncertainty, the updated requirements are expressed using 5 criteria (spatial resolution, temporal resolution, measurement uncertainty, stability, timeliness) with values for goal (ideal value), breakthrough (intermediate) and threshold (minimum) requirements (See General definitions section).

The requirements are summarized in Table 3, with the exception of stability which is not specified for sea ice thickness. The CryoSat-2/SMOS data record is not specified as a CDR, however here, it is tested against these requirements anyway.

Table 3: Update requirements for sea ice thickness climate data records (WMO, 2022).

	Horizontal Resolution	**Temporal Resolution**	**Timeliness**	**Uncertainty**
Goal	1 km	Daily Year-Around	1 days	0.05 m
Breakthrough	25 km Distribution, mean & median	Weekly – Monthly Year-Around	7 days	0.1 m
Threshold	50 km	Monthly Wintertime Only	30 days	0.25 m
CryoSat-2/SMOS	25 km mean	Daily Wintertime Only	50+ day	0.30 m

The CryoSat-2/SMOS data record fulfils the breakthrough requirement for spatial resolution (25 km), and the threshold requirement for temporal resolution (daily, but only during wintertime).

The timeliness of CryoSat-2/SMOS does not meet the Threshold target. The delay is caused by the computation of a background field. Faster delivery is possible by using near-real time data from CryoSat-2 and SMOS, which are not utilized for this data record. The size of this background field, and thus the achievable timeliness with regular Cryosat-2 and SMOS, is the target of a product development for the next version of this data record.

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