FDR4ALT

Validation Report Document : Sea-Ice TDP

CLS-ENV-NT-23-0418
Issue 4.1 – 03/07/2023

Public

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CHRONOLOGY ISSUES

Issue	Date	Object
1.0	17/05/22	Draft version for Phase 2 PM#1
2.0	02/12/22	Intermediate version for Phase 2 PM #1 (80% completed for ENVISAT)
3.0	02/05/23	Final version for Final Review
4.0	23/05/23	Final version for Final Review with RIDs implemented
4.1	03/07/23	Final version: document divided into distinct reports

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1 Introduction

This document has been written in the frame of the FDR4ALT project, ESA contract N°4000128220/19/I-BG. It is a deliverable of task 4 of the project and is identified as [D-4-02].

1.1 The FDR4ALT Project

In the framework of the European Long Term Data Preservation Program (LTDP+) which aims at generating innovative Earth system data records named Fundamental Data Records (basically level 1 altimeter and radiometer data) and Thematic Data Records (basically level 2+ geophysical products), ESA/ESRIN has launched a reprocessing activity of ERS-1, ERS-2 and ENVISAT altimeter and radiometer dataset, called the FDR4ALT project (Fundamental Data Records for Altimetry). A large consortium of thematic experts has been formed to perform these activities which are:

1) To define products including the long, harmonized record of uncertainty-quantified observations.

2) To define the most appropriate level 1 and level 2 processing.

3) To reprocess the whole times series according to the predefined processing.

4) To validate the different products and provide them to large communities of users focused on the observation of the atmosphere, ocean topography, ocean waves, coastal, hydrology, sea ice, ice sheet regions.

1.2 Purpose and scope of the validation report

After the FDR/TDP definition step and all benchmarking (Round Robin) between standard solutions addressed by each expert group, comes the production and validation step.

The objective of this document is to provide a validation report for the Sea-Ice TDP, following the strategy defined in the Validation Plan Document [D-4-01]. Note that to avoid heavy documents, the validation reports have been divided: there is one validation report for the FDRs (ALT FDR and MWR FDR) and one validation for each of the six TDPs. This document therefore contains only results for the **Sea-Ice TDP**.

This document describes in detail the validation that has been performed for the Sea-Ice TDP to assess the performances of the FDR4ALT final products. The validation covers the full lifespan of the missions and therefore includes long-term analysis, as well as cyclic analysis or targeted analysis that are relevant for this TDP.

2 Terminology

This section aims at defining clearly the terminology used in the FDR4ALT deliverables.

- **Product** refers a specific type of file, defined and described by a dedicated handbook, and designed for a clear purpose (the FDR4ALT project, the REAPER project, …). It is a “container”. One product refers to one file. The use of plural is designed to refer to a group of files, for instance the Thematic Data Products. “FDR4ALT products” will usually refer to all TDPs and FDRs, i.e., the outputs of the whole project. Note that the word “product” does not imply any notion of start date or end date, whereas “dataset” does.
- **File** can be used to refer to one single product or any other file that is not a product.

- **Parameter or variable** refers to a product's field, i.e., the content of the product. For instance, the sea level anomaly is a parameter of the Ocean & Coastal Thematic Data Products.
  Dataset can be used to refer to any group of data, not necessarily products. However, in the context of this project, it will often be used to refer to a sub-ensemble of products, on a specific period of time or a specific geographic area. For instance, the TDS (test dataset) refers to a dataset of 3 years of test products.

3 Sea-Ice Thematic Data Products

3.1 Introduction

This section describes the results of the Sea-Ice Thematic Data Products validation. The subsections cover a list of the validation datasets, the metrics used for indicating the data quality and the validation results.

3.2 Validation datasets

This section briefly lists and describes the datasets used for the validation. The validation makes use of the CCI+ Round Robin Data Package, for which further descriptions can be found in [**RD 13**], the CCI+ validation publication, submitted before final version of this document. The necessary processing steps for validation data are also described in detail in that document.

Airborne

- Airborne electromagnetic [AEM and AEM_frb, sea ice thickness and sea ice freeboard] sounding campaigns, [**RD 8**], as well as coincident airborne laser scanner data.
- NASA Operation IceBridge data [OIB-IDCS4, OIB-ql, sea ice thickness, sea ice freeboard, snow depth], [**RD 1**, **RD 3**, **RD 4**]

Drifting buoys

- CRREL ice mass balance buoys [IMB, sea ice thickness, snow depth], [**RD 9**]
- North Pole Drifting stations [NP, sea ice draft], [**RD 13**]]

Moorings

- Norwegian Polar Institute moored upward looking sonars [NPI, sea ice draft], [**RD12**]
- Alfred Wegener Institute moored upward looking sonars [AWI_ULS, sea ice draft], [**RD 6**]
- Beaufort Gyre Exploration Project [BGEP, sea ice draft] moored upward looking sonars, [**RD 5**]

Ship based measurements

- Arctic Shipborne Sea Ice Standardization Tool [ASSIST, sea ice thickness, snow depth] measurements, [**RD 11**]
- SCAR Antarctic Sea Ice Processes and Climate program ship-based observations [ASPeCt, sea ice thickness, snow depth], [**RD 10**]

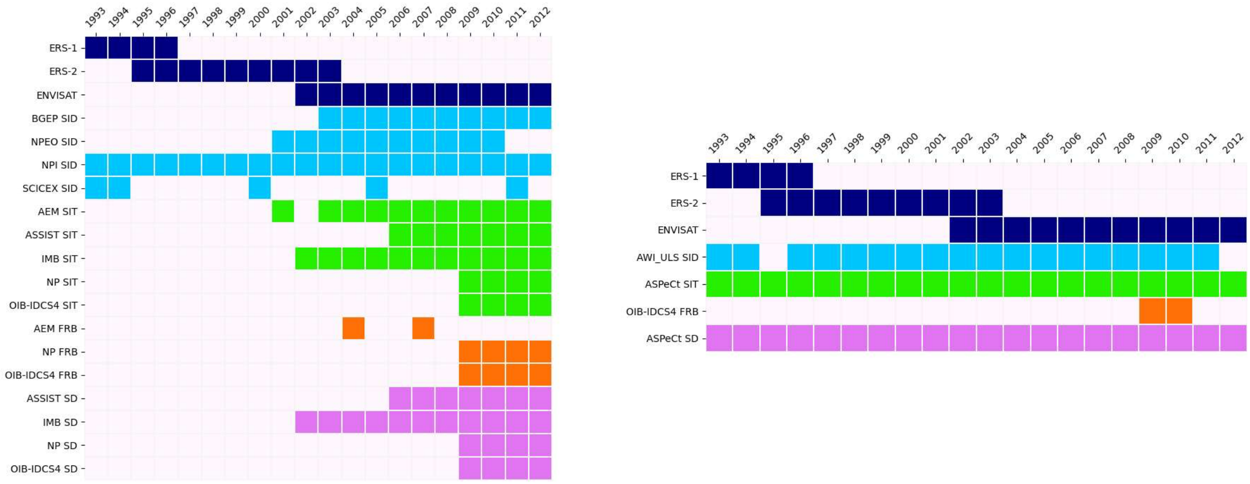
Submarines

- Submarine sea ice draft data from SCICEX [SCICEX, sea ice draft], [**RD 7**]

Collections

- Unified Sea Ice Thickness Climate Data Record [for supportive use, contains many of the above-mentioned datasets, sea ice draft, freeboard and thickness], [**RD 2**]

Table 1: Temporal coverages of the validation datasets. Left for Arctic and right for Antarctic. The rows are organized per product source (e.g. BGEP for the Beaufort Gyre Exploration Project upward looking sonars) and the respective geophysical variable, SID: sea ice draft, SIT: sea ice thickness, FRB: sea ice freeboard and SD: snow depth.



Temporal coverage of the validation data can be seen in Table 1 for the Arctic (left) and for the Antarctic (right). The amount of available validation data grows towards the end of the ENVISAT period, especially for the northern hemisphere. Seasonal/monthly and spatial coverage varies also greatly, as can be seen from Figure 3-1 and Figure 3-2. Some datasets are collected only during spring (OIB-IDCS4) or fall (ASSIST). Spatially the Arctic data is concentrated more towards the Western side of the Arctic.

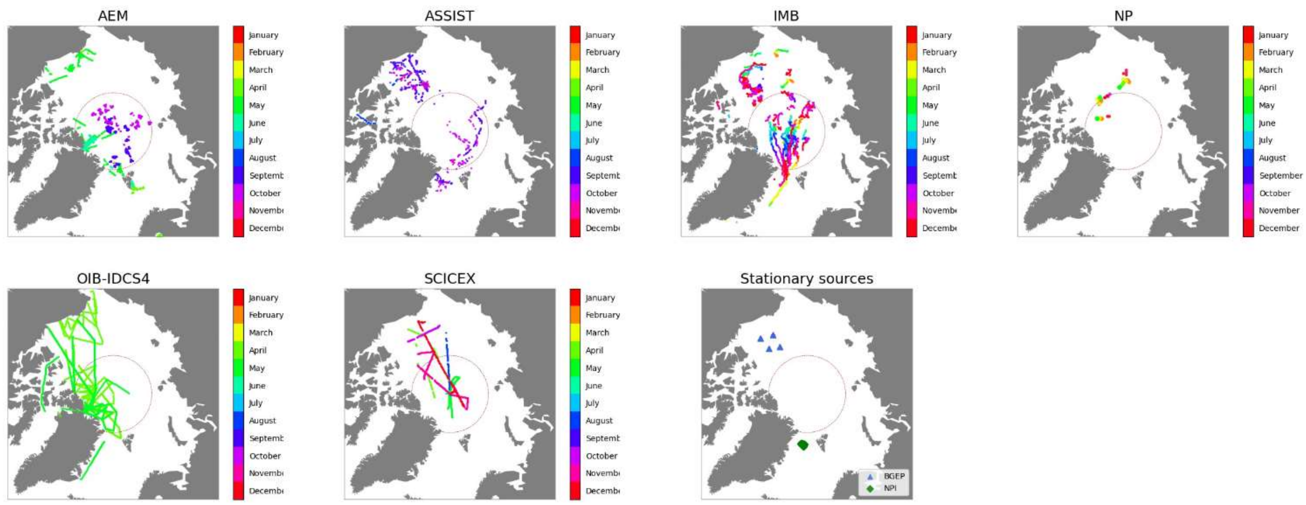


Figure 3-1: Spatial and monthly extents of the validation datasets per data source for the Arctic. The dashed line depicts the 81.5°N, which is the northern limit for the satellite coverage.

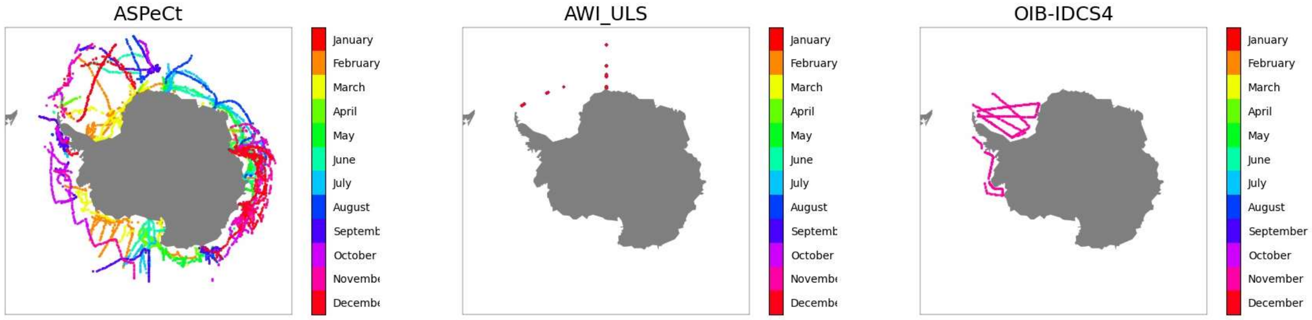


Figure 3-2: Spatial and monthly extents of the validation datasets per data source for the Arctic. The dashed line depicts the 81.5°S, which is the southern limit for the satellite coverage.

3.3 Validation procedure and metrics

The validation data has been co-located with the Sea-Ice TDP products. For these co-located pairs of product and validation data, distributions and their differences are derived and used to estimate the bias. Essentially the steps are as follows:

1. Co-locating the validation data with the satellite data with a search radius and a time window.
2. Converting the product to match the validation data geophysical variable.
3. Compare distributions with scatterplots and describing statistics.
4. Estimate the importance and reliability of the results.

One of the main difficulties concerns the conversion of the parameters to make theme comparable (point 2 above). Indeed, as shown in the previous section, the in-situ measurements do not provide the radar freeboard measured by the altimetry but, according to the methodology, they could provide the ice draft, ice freeboard, total freeboard (ie, including the snow depth), sea ice thickness with or without the snow included. In order to make these dimensions comparable, we have to convert them using an auxiliary snow depth parameter.

The snow depth that has been used in the context of the project are climatologies: the Warren 99 climatology for the Arctic [**RD 15**] and the Altimetric Snow Depth (ASD) climatology for Antarctic [**RD 16**].

These choices were conditioned by the absence of alternative solutions at the beginning of the FDR4ALT project, but they raise important problems: in particular, Warren's climatology is only valid for the central Arctic Ocean, and these climatologies cannot be representative of the important evolution of the climate in the polar regions all along ERS-1, ERS-2 and ENVISAT periods. The inadequacy of these snow solutions will of course affect the quality of the validation presented below.

On the other hand, other solutions are being developed, and in particular the Arctic Snow LG model [**RD 18**, **RD 17**] which provides much more consistent estimates. Validations based on this model can be found in Bocquet et al 2022 [**RD 14**].

Finally, it is important to note that the sea ice thickness delivered in the FDR4ALT product can be easily re-calculated from another snow solution using the following equation:

$$SIT = \frac{\rho_w}{\rho_w - \rho_i} FB_{Ku} + \frac{\rho_w (1 + 0.00051\, \rho_s)^{1.5} - \rho_w + \rho_s}{\rho_w - \rho_i} SD$$

3.4 Validation results

3.4.1 ENVISAT

Arctic

All ENVISAT variables compare best with airborne (AEM, OIB-IDCS4, OIB-ql, Figure 3-3 and Figure 3-4) and draft (BGEP, NPI, SCICEX, Figure 3-4) data. This holds especially for sea ice thickness (OIB-ql) with 0.68 correlation (Figure 3-5) and for draft, where correlations range from 0.53 (NPI) to 0.82 (BGEP) (Figure 3-4). Interestingly the correlations and variations are not in a consistent order between the validation products, but whereas AEM (with very little data) or OIB-IDCS4 seem to be better fits than OIB-ql for sea ice freeboard (Figure 3-3), OIB-ql would seem to match better for sea ice thickness (Figure 3-5). This might be due to handling of snow by the validation data set, or due to differences in sampling, and is yet another example that validation data should be handled with caution.

The draft comparisons, in Figure 3-4, might be the most representative comparison for the gridded monthly products due to their temporal extent and representative sampling scheme. Although draft is often measured with a moored instrument, as ice drifts, the moored instrument samples in a way a large set of ice spatially. Especially the drafts from BGEP show a good match with ENVISAT draft.

The poorest match is with ASSIST (correlation of –0.02, and largest differences with the individual ENVISAT values), and also for IMB (Figure 3-5). For ASSIST the data set size is small, and dominated by the minimum value, meaning we would not consider these results. The IMB data set is more extensive, and the data collection method quite sophisticated, but as the instrument samples only one location on the ice, it might not be representative of a large area, although the installation location is chosen so that it should be representative of the surroundings.

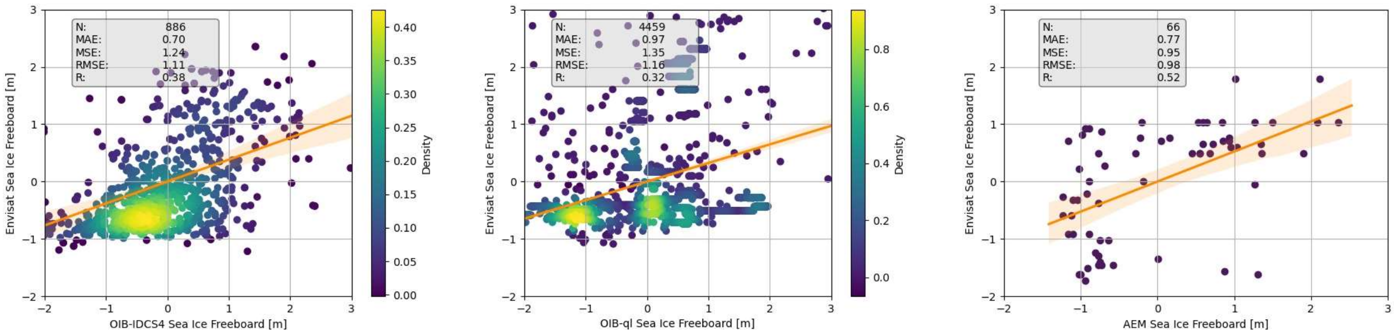


Figure 3-3 : Sea ice freeboard comparisons for ENVISAT (y-axis) against validation data (x-axis) in the Arctic. Left with OIB-IDCS4, middle OIB-ql and right AEM.

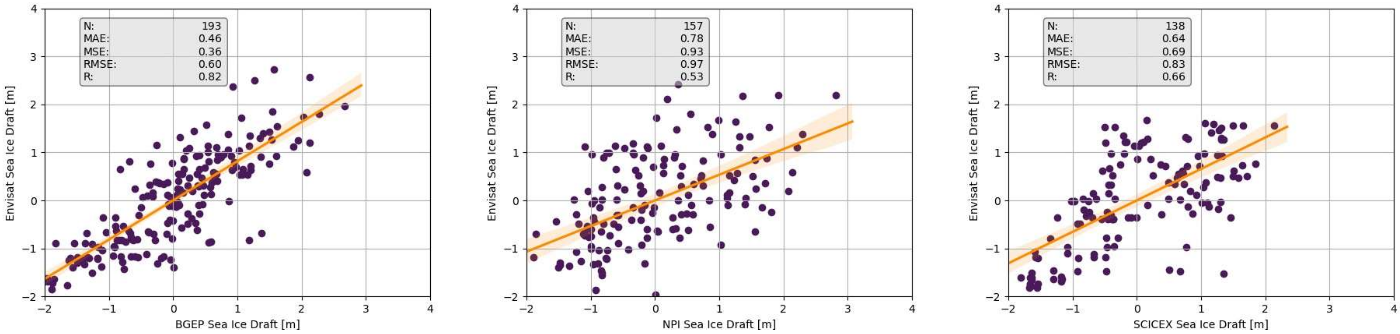


Figure 3-4 : Sea ice draft comparisons for ENVISAT (y-axis) against validation data (x-axis) in the Arctic. Left with BGEG, middle NPI and right SCICEX

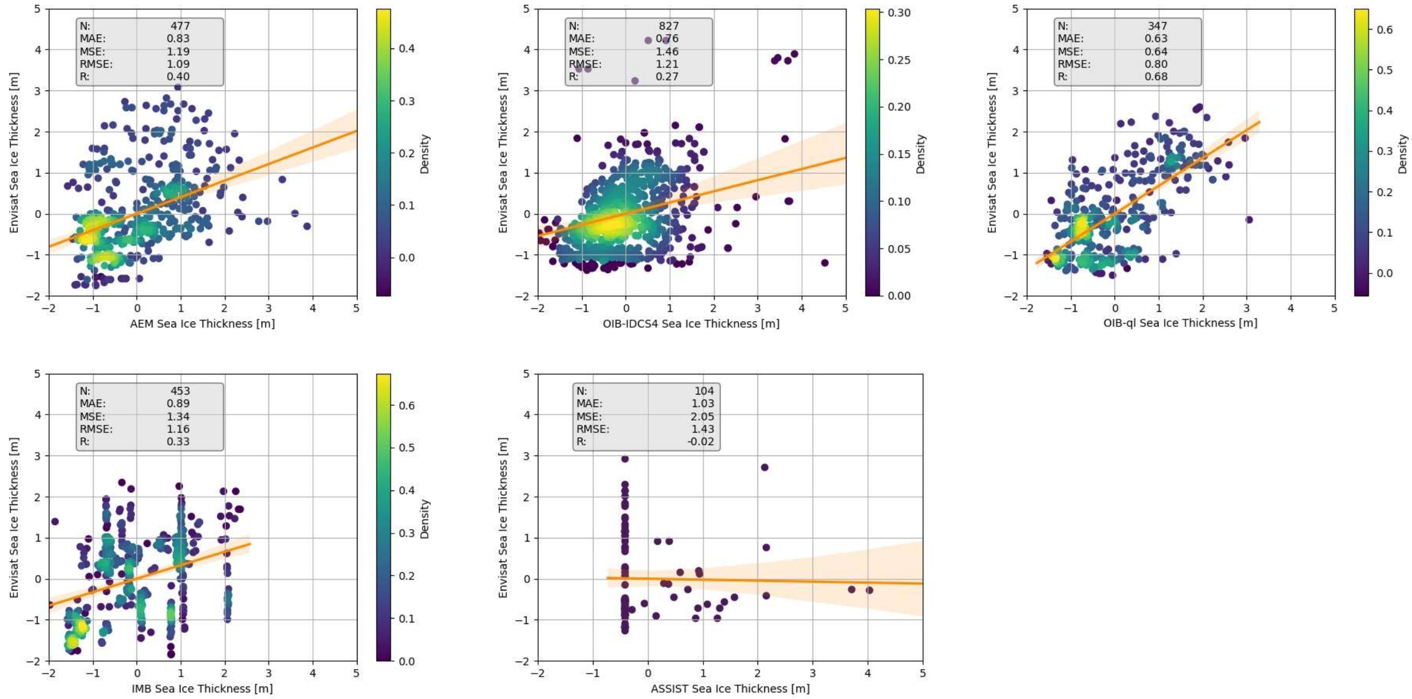


Figure 3-5 : Sea ice thickness comparisons for ENVISAT (y-axis) against validation data (x-axis) in the Arctic. Top row: left with AEM, middle OIB-IDCS4 and right OIB-ql. Bottom row: left with IMB and right with ASSIST

<u>Antarctic</u>

For Antarctic there is not much validation data. For ENVISAT period we found only OIB and ASPeCT data. For OIB the correlation is 0.41 for the total freeboard (ice and snow freeboard) and for ASPeCT 0.28 for the sea ice thickness Figure 3-6. These both have quite some scatter in the values. For ASPeCT there seems to be a concentration of values around –0.5m, similarly to ASSIST, but with the difference that here also ENVISAT has a large amount of small values (<0.5m).

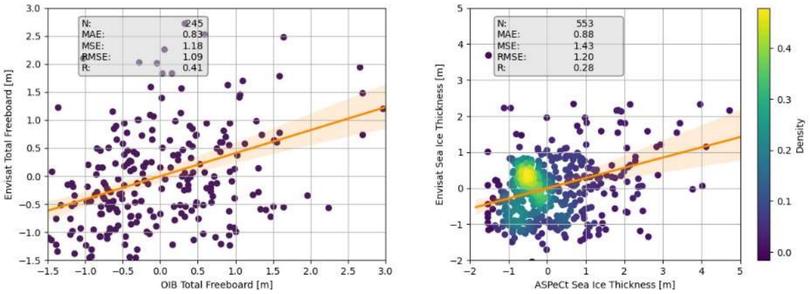


Figure 3-6 : Comparisons for ENVISAT (y-axis) against validation data (x-axis) in the Antarctic. Left with OIB total freeboard and right ASPeCT sea ice thickness.

3.4.2 ERS-2

Arctic

ERS-2 seems to match better with the NPI draft and AEM sea ice thickness measurements, with correlation values close to 0.5, than with the SCICEX data, where the correlation is negative (Figure 3-7). Even for these better fitting validation data the data points are scattered, especially for AEM, and the magnitude of differences is notable compared to the data values.

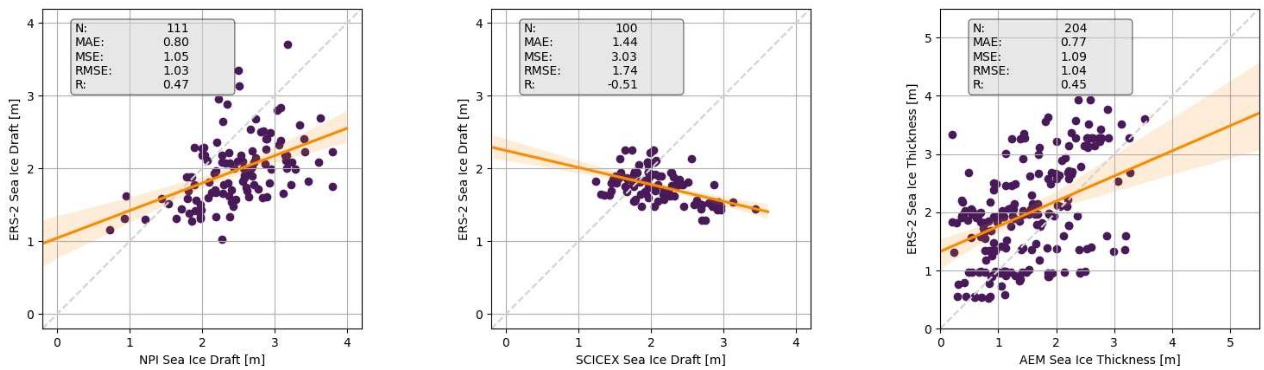


Figure 3-7: Comparisons for ERS-2 (y-axis) against validation data (x-axis) in the Arctic. Left with NPI sea ice draft, middle with SCICEX sea ice draft and right with AEM sea ice thickness.

Antarctic

In the Antarctic, the AWI ULS draft and ASPeCt sea ice thickness correlate rather poorly (~0.25) with the ERS-2 data (Figure 3-8). For draft, it would seem ERS-2 is missing most of the thickest ice. For sea ice thickness it is clear that ASPeCt has a great number of samples focused around 0.5m thick ice, with which ERS-2 does not seem to agree.

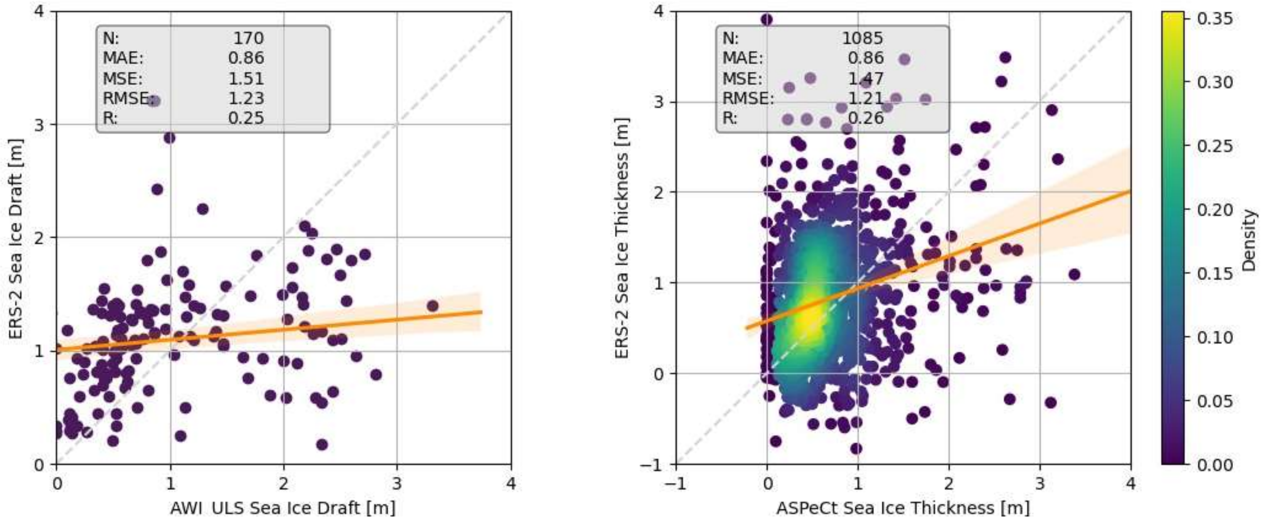


Figure 3-8: Comparisons for ERS-2 (y-axis) against validation data (x-axis) in the Antarctic. Left with AWI ULS sea ice draft and right with ASPeCt sea ice thickness.

3.4.3 ERS-1

<u>Arctic</u>

ERS-1 has only one validation dataset to be compared against, NPI sea ice draft (Figure 3-9), and the number of this data is hardly enough for significant comparisons. However, the few datapoints have a decent correlation (0.70).

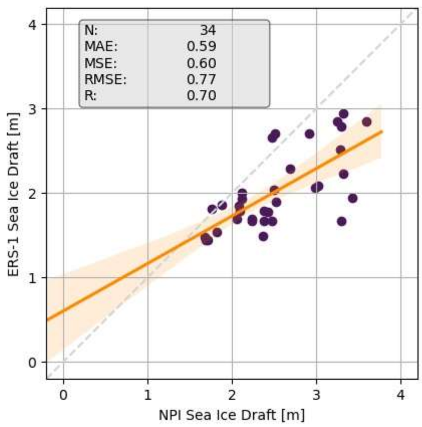


Figure 3-9: Comparisons for ERS-1 (y-axis) against validation data (x-axis) in the Arctic. The validation data here is the NPI sea ice draft.

<u>Antarctic</u>

In the Antarctic ERS-1 has more validation data thanks to the ASPeCt cruises. In addition to ASPeCt snow depth and sea ice thickness, there is also a scarce set of AWI ULS measurements (Figure 3-10). Similarly to the Arctic, the draft dataset has a good correlation, with ERS-1 constantly slightly overestimating the draft. For snow depth, ASPeCt has caught more variability in snow depths compared to the snow climatology (ASD) used in the ERS-1 product, which is much expected given the respective natures of these datasets. Once again, ASPeCt is heavily pronounced on ice thicknesses less than 1.0 m, whereas ERS-1 estimates the ice to have more variability in thickness.

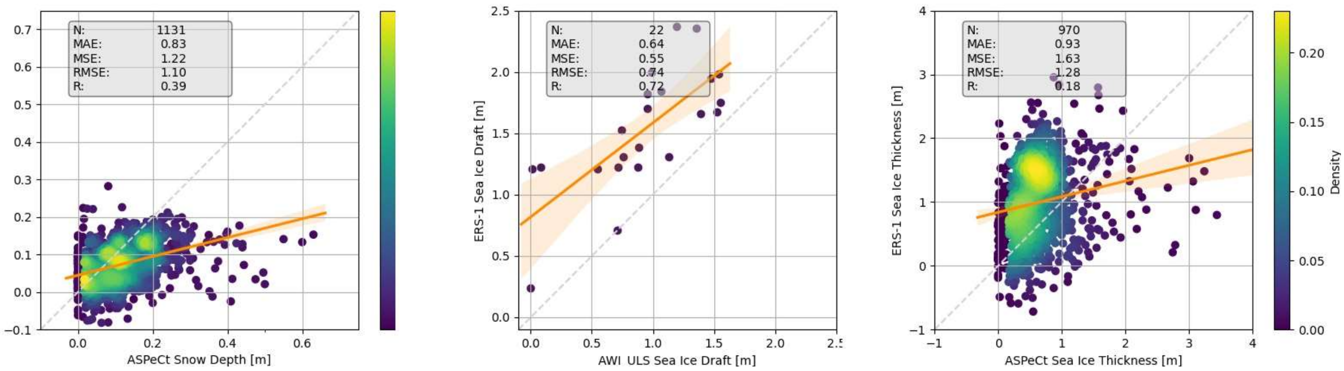


Figure 3-10: Comparisons for ERS-1 (y-axis) against validation data (x-axis) in the Antarctic. Left with ASPeCt snow depth, middle with AWI ULS sea ice draft and right with ASPeCt sea ice thickness.

3.5 Conclusions

As pointed out in earlier sections, the validation data varies in temporal and spatial extents. OIB-IDCS4 covers only spring months, meaning it is only representative of these months, and mainly over multiyear ice due to its spatial extent. Also the sampling strategy of the validation data varies. ASSIST and ASPeCt, which contain ship-based observations, most likely oversample thin ice, as thick ice would be much harder or impenetrable for the ships to go through. IMB measurements, although temporally and spatially representative in Figure 3-5 , measure only one location on one ice floe over the sampling period. Stationary measurements, like BGEP and others (Figure 3-4), are good in a sense that they cover long periods of time, and although they stay spatially in the same location, they sample all the ice that moves over the station, creating a representative overview of the ice distribution.

In general, the Sea-Ice TDP seemed to best match with draft data. Draft data used here comes mainly from two types of sources: moored ULS instruments (AWI ULS, BGEP, NPI) and submarine based ULS instrument (SCICEX). Both types of sources have good spatial sampling of varying types of ice, and especially the moored instruments have a good temporal coverage throughout the whole year. Here it is noteworthy to point out, that in order to get sea ice draft from the product variables, a snow estimate is needed to convert the values from radar freeboard (and sea ice thickness) to draft. This introduces an extra source of uncertainties in the comparisons.

We also recall, as noted in section 4.2.3, that snow depth plays a very important role in the conversion of radar freeboard to ice depth or draft and that the snow used here is not representative of the snow over the entire period considered and the entire basin. For example, [**RD 14**] validates the ERS-2 and ENVISAT freeboards in the Arctic using the recently updated Snow Model LG solution [**RD 18**, **RD 17**]. Whenever possible, it is recommended to use the snow depth estimate best suited to the region or period considered to re-estimate the ice thickness from the radar freeboard delivered in this Sea-Ice TDP.

3.6 Sea-Ice type classification

3.6.1 Introduction

The purpose of this task was to update the ocean/sea-ice type flag for ERS missions to align it with ENVISAT v3.0 version. Such multi-state flag computed from 1-Hz data aims to help both oceanic and cryosphere studies in data selection. In the REAPER products, the computation used Tran et al's algorithm **[RD-19]** and generated a 3-state flag (0= open-ocean, 1= sea-ice, 2= not evaluated). This version corresponds to the first ENVISAT empirical algorithm and is no longer in-line with the latest version implemented for the ENVISAT v3.0 reprocessing. Indeed, different modifications have been made since **[RD-20; RD-21]**, such as:

- the definition of a 6-state flag with more precise description of the sea-ice nature (first-year ice, multi-year ice, wet ice and ambiguous surface associated to mixture of type) in addition to the 'open-ocean' and 'not evaluated' states
- the development of polar region-specific versions while the REAPER version was derived from arctic data and is not fully adapted to describe Antarctic sea-ice where the environmental context is different for sea-ice growth and decay from the arctic region; there is for instance no multi-year ice in the South Pole
- this REAPER version does not benefit of the changes made in regional masks from the 2012 study; a new set of seasonal and regional masks were defined for ENVISAT to avoid the cut of some local part of the sea-ice pack due to too severe boundary setting.

This section describes the results of the ERS sea-ice flag update validation. The subsections provide first an assessment of the REAPER flag and point out its anomalies, and then present the validation results after the application of the ENVISAT v3.0 version.

3.6.2 REAPER flag assessment

This assessment exercise relies on the comparison of REAPER sea-ice distribution maps with those obtained from ENVISAT v3.0 data or derived from OSISAF ice concentration data by setting a 15% threshold to split them into two categories: open-ocean or sea-ice surfaces. This threshold is commonly used to derive daily sea ice extent map as indicated in this web page (https://osisaf-hl.met.no/v2p1-sea-ice-index). Note, these maps are different from daily sea-ice area map which represents the total ocean area covered by any amount of ice (i.e. 0% threshold). We used the first setting for the comparison because altimeter data are not affected by light amount of sea-ice within its footprint and therefore cannot detect their presence. This allows to perform fairer comparison between the different flagging definitions.

Figure 3-11 shows such comparison from monthly maps over September 2002 when ERS-2 and ENVISAT flew in tandem. As we can see, there are some obvious differences between these maps even if the sea-ice extent estimations are qualitatively very consistent between them. Three issues are pointed out. First, ERS-2 map displays a very large amount of 'not evaluated' state data which corresponds to situations where the classification algorithm cannot be applied because of missing input data, either Ku-band sigma0 or brightness temperatures. Second, the Antarctica ice-shelves in the different maps are not considered in the same way. REAPER wrongly classifies them as first-year sea-ice surface while ENVISAT v3.0 does not process data at such locations thanks to information coming from a surface type flag that identifies them. Data over such surfaces are not considered either in the OSISAF processing. Finally, in the arctic region, while REAPER indicates sea-ice detection without information about the sea-ice type, ENVISAT v3.0 data distinguish different sea-ice natures allowed by its 5 meaningful classes with particularly the detection of the presence of multi-year ice within the sea-ice pack.

Concerning the first issue about the large percentage of 'not evaluated' data, Figure 3-11 illustrates the source of this feature more globally from cycle 17 data. There are two kinds of structures of 'not evaluated' data. The red tracks correspond to 1-Hz brightness temperatures at default values (DV) and this situation prevents us from applying the classification algorithm. The red dots on the surface associated to the sea-ice pack is due to 1-Hz Ku-band sigma0 at DV and are related to problems in either retracking algorithm convergence at 20-Hz or compression process to form the 1-Hz data. But in any case, this also prevents us from applying the classification algorithm and therefore to identify the sea-ice type at these locations. Note the white tracks correspond to missing orbit data. This anomaly cannot be corrected in FDR4ALT even if the classification algorithm version changes since the algorithms use the same inputs in REAPER and FDR4ALT. Note that update in the TB calibration and slight change in Ku-band sigma0 related to update in atmospheric attenuation correction in FDR4ALT will not change the DV status.

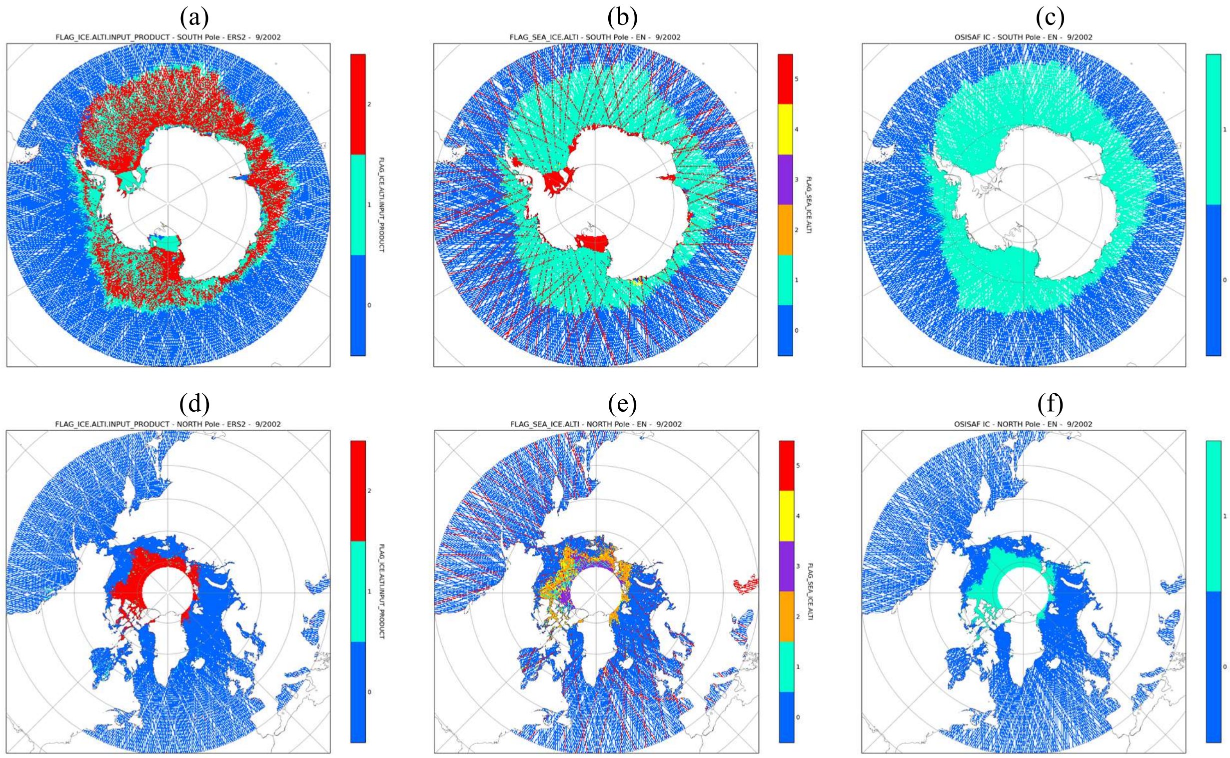


Figure 3-11: Comparison of different sea-ice flags over September 2002: (top panels) for the Antarctic region and (bottom panels) for the arctic region. (a) and (d) concern ERS-2 REAPER flag; (b) and (e) concern ENVISAT v3.0 flag; (c) and (f) concern a flag derived from OSISAF sea-ice concentration.

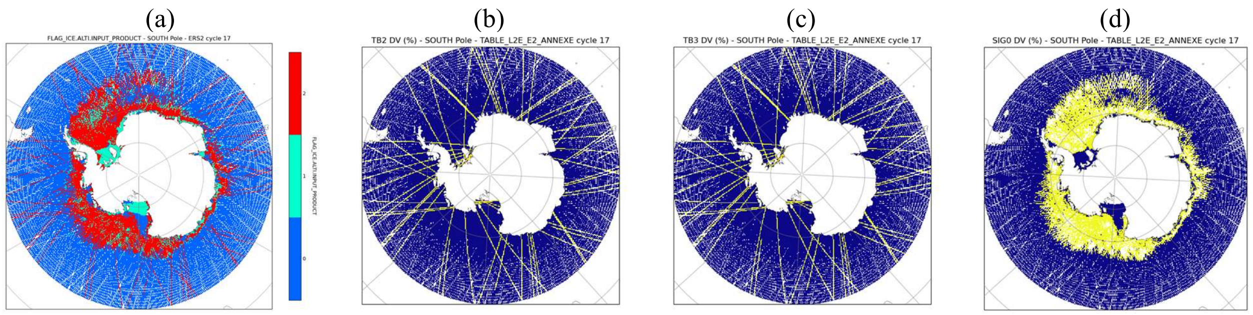


Figure 3-12: (a) REAPER sea-ice flag and locations of default values (DV) displayed as yellow dots for (b) 23.8 GHz TB, (c) 36.5 GHz TB, and (d) Ku-band sigma0 for cycle 17.

Concerning the second issue related to the classification over the ice-shelves, the erroneous setting in REAPER flag is related to the use of a 4-state surface type flag that does not allow the identification of such surface type. It is computed using the TERRAINBASE model with the following identification: 0= open ocean s or semi-enclosed seas; 1= enclosed seas or lakes; 2= continental ice; 3= land. ENVISAT version uses a more complete description that combines different information sources as follows: 0= open ocean, 1= land, 2= continental water, 3= aquatic vegetation, 4= continental ice snow, 5= floating ice, 6= salted basin. Figure 3-13 shows the differences between these two surface type flags for the Antarctic region. This anomaly will be corrected in the updated ERS-2 flag in FDR4ALT by taking the correct surface type mask from ENVISAT chain.

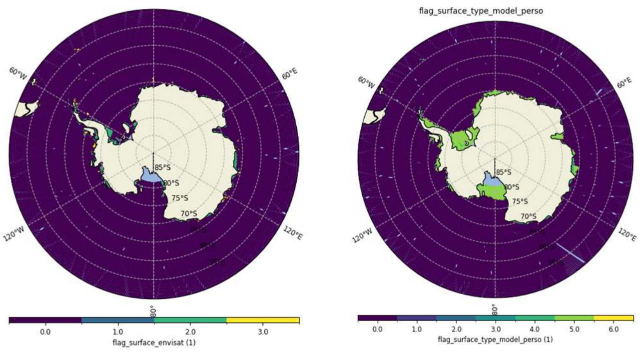


Figure 3-13: Comparison of two surface type flags: (left) a 4-state flag as used for REAPER reprocessing and (right) a 7-state flag as used in the sea-ice classification algorithm defined for ENVISAT.

3.6.3 Validation results

Figure 3-14 and Figure 3-15 show the ERS-2 maps comparison between the REAPER and the FDR4ALT flag versions for respectively the Antarctic and the arctic areas for 1 cycle of data. The cycle is different for each polar region to display a period of maximum extent of the sea-ice pack during their respective winter seasons. The map corresponds to a grid of 25 km x 25 km where each box displays the colour associated to the most populated class. Note in Figure 3-11, the maps were derived with this approach. In panels (a) and (c), the 'not evaluated' class data are included in the map computation while in panels (b) and (d) they are not considered allowing to see the second populated group when the sea-ice type is determined. Excepted for the erroneous classification over the ice-shelves that is corrected in the FDR4ALT data, the results are very similar as expected. It is not in this region that the ENVISAT v3.0 version brings the most improvement.

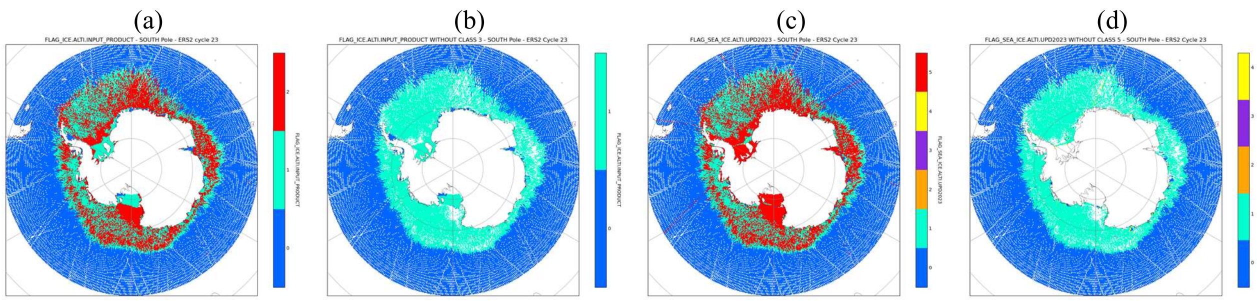


Figure 3-14: Comparison of REAPER sea-ice flag in (a) and (b) with updated ERS-2 flag based on ENVISAT v3.0 algorithm in (c) and (d). In panels (b) and (d), the 'not evaluated' class data have not been considered in the map computation while they were included to generate maps in (a) and (c). This comparison was performed on cycle 23 of ERS-2 for the Antarctic region.

In the arctic region, despite the large percentage of data for which the sea-ice type cannot be determined because of Ku-band sigma0 values at DV in panel (c), we can clearly see that a multi-year ice area is realistically delineated in panel (d) during the winter season as expected from FDR4ALT ERS-2 data. It is not possible to quantitatively assess the performance of this discrimination by sea-ice type as done recently for Sentinel-3A flag validation activities because OSISAF sea-ice type products used as reference are available only since 2005 (https://osi-saf.eumetsat.int/products/osi-403-d). However, Reasonable regional and seasonal coherence is attained. The sea-ice type distribution maps show stability in the sea ice class areas between contiguous maps during winter. The dominant sea ice type distributions show realistic features with multi-year ice located mainly in the central Arctic Ocean, north of Greenland and the Canadian Archipelago. First-year ice data are in the peripheral areas such as Barents Sea or Hudson Bay for instance. The ambiguous pixels are located in the neighbourhoods of the boundaries between two dominant sea ice type zones. Same results are observed also from FDR4ALT ERS-1 data. Note also, the bad handling of the FDR4ALT data over the Caspian Sea could be improved in the future.

The large number of sigma0 values at DV for ERS missions limits the potential of this sea ice type mapping capability for climate monitoring. As seen in Figure 3-16 for cycle 23 during summer period, over most of the sea-ice area the determination of the sea-ice nature cannot be done. A lot of boxes are empty, without identified sea-ice data (i.e., class other than ‘not evaluated’). Therefore, it is very complicated to perform analysis of seasonal variability of the global sea ice extent, or evaluation of FYI and MYI covers change through time or monitoring of the seasonal transitions: melt onset and freeze-up onset which can provide information on summer melt duration. As this was done from ENVISAT flag time-series.

To tackle this issue, different actions could be envisaged:

- Identification of the source of the sigma0 values at DV, is it a problem of convergence in the retracking algorithm at 20-Hz? or some bad setting in the compression method that is used to form the 1-Hz data?
- Use of better retracking algorithm version if the problem comes from the retracking approach.
- Use of 20-Hz data instead of 1-Hz data to perform this classification on more available data.

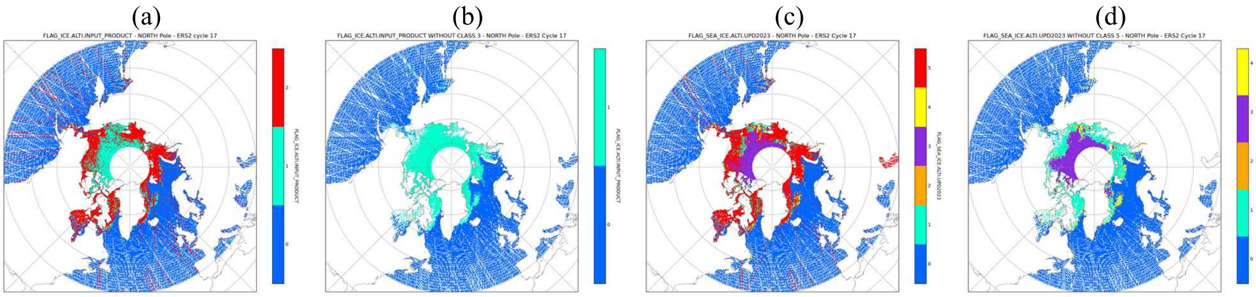


Figure 3-15: Same as Figure but with ERS-2 data from cycle 17 for the arctic region.

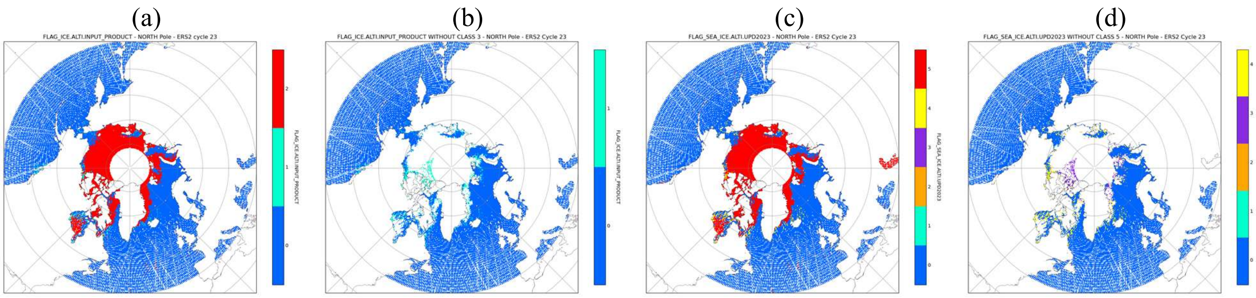


Figure 3-16: Same as Figure 3-15 but with data from cycle 23.

There is another issue that was highlighted when analysing the time-series of cyclic maps from ERS-2 FDR4ALT flag. Figure 3-17 shows that the seasonal masks defined for ENVISAT period is not fully suitable for

ERS periods as it was seen also for Sentinel-3A flag. The left panel displays indeed some sharp boundaries in the sea-ice edges with respect to latitude that is well correlated with the mask delimitation. The purpose of these seasonal masks was to limit the number of false sea-ice detection in the open-ocean area. But as seen here, the masks defined for ENVISAT data are a little bit too severe for ERS periods and leads to strong cut in the sea-ice pack extent. It is recommended to adapt the masks to ERS data as it was done for Sentinel-3A.

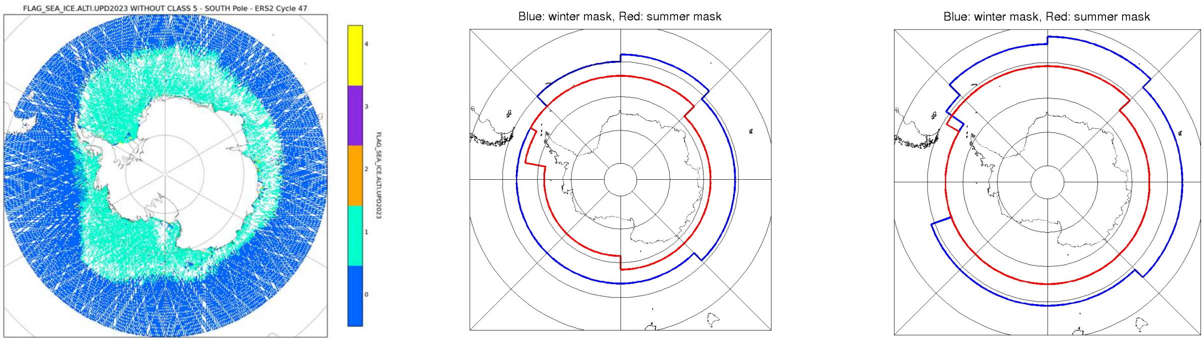


Figure 3-17: (left) Map of updated ERS-2 flag from cycle 47 for the Antarctic region with truncated areas in some parts of the sea-ice pack. (Middle) seasonal masks applied within ENVISAT sea-ice classification algorithm; (Right) masks defined for Sentinel-3A version.

Finally, the last validation result concerns the continuity between ERS-1 and ERS-2 flags distributions from FDR4ALT dataset. Figure 3-18 and Figure 3-19 show very good consistency in the sea-ice type distributions between ERS-1 and ERS-2 flags from the new dataset when data from the 'not evaluated' class are not used to generate the different maps. This assessment was performed for two periods of 1-month taken during the tandem phase between the 2 missions: 1-month chosen during summer period to display the lowest sea-ice extent and 1-month taken during wintertime where the sea-ice extent is at its maximum.

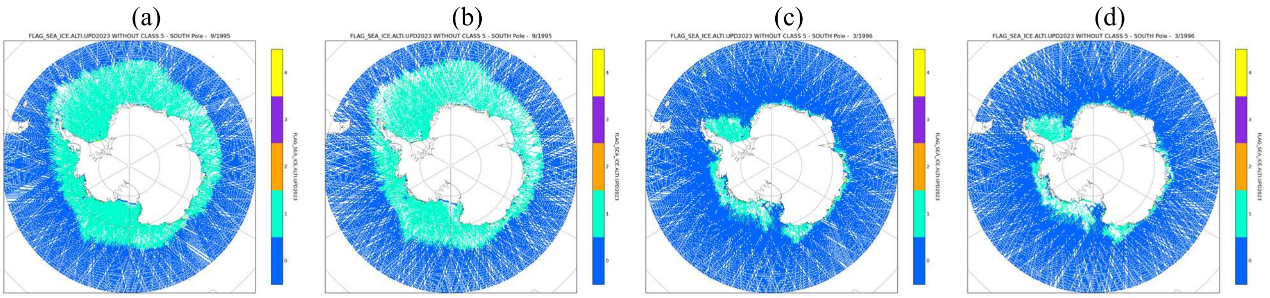


Figure 3-18: Comparison of updated sea-ice flags for ERS-1 and ERS-2 over 2 periods of 1-month (September 1995 and March 1996) acquired during their tandem phase over the Antarctic region.

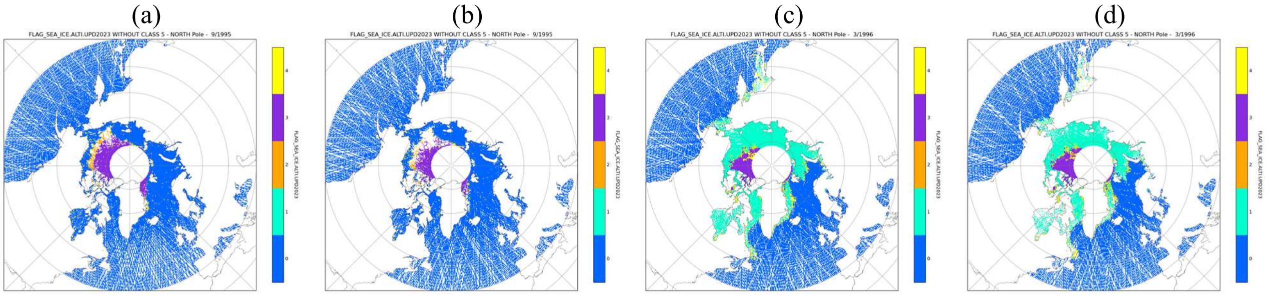


Figure 3-19: Same as Figure over the arctic region.

3.6.4 Conclusions and remarks

Concerning the sea-ice type classification, the validation results show that the sea-ice type distributions are very consistent now for the 3 missions handled by the FDR4ALT project. The main improvement for the ERS missions lies in the delimitation of multi-year ice area within the sea-ice pack extent. The alignment of the ERS classification algorithm on the ENVISAT v3.0 version allows us also to correct for erroneous classification of the data over Antarctica ice-shelves. However, the issue related to the large number of 'not evaluated' data over the sea-ice pack by the classification algorithm for the ERS missions remains and is caused by 1-Hz Ku-band sigma0 values at default value. Different actions are proposed to tackle this problem which represents a limitation of the usefulness of the ERS data for climate monitoring. Further adaptation of the classification algorithm to ERS data is also recommended and concerns mostly the seasonal geographical masks applied within the approach.

This algorithm was originally designed for application to 1-Hz data. In the FDR4ALT dataset, the standard rate is 20-Hz. Therefore, the decision was made by the project to duplicate the 1-Hz flag values into 20-Hz locations; but direct computation at 20-Hz rate should be considered for next reprocessing version. A better option might be to design directly a classification algorithm based on 20-Hz data by using additional information now available such as waveform classification or SST information, etc … , in order to remove the need of the seasonal geographical masks in the process and also to add identification of more sea-ice type in the flag. Correction in the handling of the data from the Caspian Sea should also be considered. This is valid for ERS missions but also for ENVISAT.

Last point concerns ENVISAT data, the FDR4ALT flag is a copy of the v3.0 reprocessing flag while the FDR4ALT project performed several updates concerning the Ku-band sigma0 (values coming from the adaptive retracking and update of atmospheric attenuation correction applied) and the brightness temperatures (update in their calibration). Therefore, inputs of the classification algorithm and classification flag provided to users are no more coherent. Some computation adaptation based on FDR4ALT data should be considered in the future along with computation of the flag after cycle 64. Indeed, in the ENVISAT v3.0 products the flag is at default value after the loss of the S-band channel, but this incident has no impact on this flag computation. Completeness of the time-series should be envisaged to provide to users this flag up to the end of the mission: from January 2008 to April 2012.

3.7 Reference documents

RD 1	Kwok, R., Kurtz, N.T., Brucker, L., Ivanoff, A., Newman, T., Farrell, S.L., King, J., Howell, S., Webster, M.A., Paden, J., Leuschen, C., MacGregor, J.A., Richter-Menge, J., Harbeck, J., Tschudi, M., 2017. Intercomparison of snow depth retrievals over Arctic sea ice from radar data acquired by Operation IceBridge. The Cryosphere 11, 2571–2593. https://doi.org/10.5194/tc-11-2571-2017
RD 2	Lindsay, R. and A. J. Schweiger. 2013, updated 2017. Unified Sea Ice Thickness Climate Data Record, 1947 Onward, Version 1. [all]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: https://doi.org/10.7265/N5D50JXV. [11-09-2021].
RD 3	NASA Operation IceBridge Data Set. Available from: ftp://n5eil01u.ecs.nsidc.org/SAN2/ICEBRIDGE/IDCSI4.001/
RD 4	2016, updated 2019. IceBridge Sea Ice Freeboard, Snow Depth, and Thickness Quick Look, Version 1. [all]. doi: https://doi.org/10.5067/GRIXZ91DE0L9. [11-10-2021]. ftp://n5eil01u.ecs.nsidc.org/SAN2/ICEBRIDGE_FTP/Evaluation_Products/IceBridge_Sea_Ice_Freeboard_SnowDepth_and_Thickness_QuickLook/Documentation

RD 5	BGEP: https://www2.whoi.edu/site/beaufortgyre/data/buoy-data-from-the-bgep- project/
RD 6	Behrendt, Axel ; Dierking, Wolfgang ; Fahrbach, Eberhard Witte, Hannelore (2013): Sea ice draft measured by upward looking sonars in the Weddell Sea (Antarctica). PANGAEA, https://doi.org/10.1594/PANGAEA.785565, Supplement to: Behrendt, A et al. (2013): Sea ice draft in the Weddell Sea, measured by upward looking sonars. Earth System Science Data, 5(1), 209-226, https://doi.org/10.5194/essd-5-209-2013
RD 7	SCICEX Science Advisory Committee. 2009, updated 2014. SCICEX: Science Ice Exercise Data Collection. Boulder, Colorado USA: National Snow and Ice Data Center. http://dx.doi.org/10.7265/N5930R3Z.
RD 8	AIR_EM: ftp://sidads.colorado.edu/pub/DATASETS/NOAA/G10006/
RD 9	Perovich, D., J. Richter-Menge, and C. Polashenski, Observing and understanding climate change: Monitoring the mass balance, motion, and thickness of Arctic sea ice, http://imb-crrel-dartmouth.org , 2021.
RD 10	Worby, A. P., C. Geiger, M. J. Paget, M. van Woert, S. F Ackley, T. DeLiberty, (2008). Thickness distribution of Antarctic sea ice. J. Geophys. Res., 113, C05S92, doi:10.1029/2007JC004254. Data available from: http://aspect.antarctica.gov.au/data
RD 11	ASSIST: https://icewatch.gina.alaska.edu
RD12	Norwegian Polar Institute (2021). Monthly mean sea ice draft from the Fram Strait Arctic Outflow Observatory since 1990. [Dataset]. https://doi.org/10.21334/npolar.2021.5b717274.
RD 13	Skourup et al. Dual-hemisphere sea ice freeboard and snow depth data package from multiple data sources for evaluation and product inter-comparison of satellite altimetry, in prep
RD 14	Bocquet, M., Fleury, S., Piras, F., Rinne, E., Sallila, H., Garnier, F., and Rémy, F.: Arctic sea ice radar freeboard retrieval from ERS-2 using altimetry: Toward sea ice thickness observation from 1995 to 2021, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2022-214
RD 15	Warren, S. G., Rigor, I. G., Untersteiner, N., Radionov, V. F., Bryazgin, N. N., Aleksandrov, Y. I., and Colony, R.: Snow Depth on Arctic Sea Ice, Journal of Climate, 12, 1814–1829, https://doi.org/10.1175/1520-0442(1999)012<1814:SDOASI>2.0.CO;2, 1999.
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RD 20	Tran N., A. Vernier and F. Ardhuin: " WOOPI project: Classification of polar sea-ice – WP1000 report", Technical report CLS-DOS-NT-11-152, 3rev.0 - 03/09/2012, 2012.
RD 21	Tran N.: "ENVISAT ESL Phase-F: Tuning activities for ENVISAT reprocessing baseline v3.0 (wind, SSB, rain and ice)", Technical report CLS-SPA-17-0069, 1rev0-09/05/2017.

Appendix A - FDR4ALT deliverables

The table below lists all FDR4ALT deliverables with their respective ID number and confidentiality level.

Document	ID	Confidentiality Level
Products Requirements & Format Specifications Document	[D-1-01] [D-2-02]	Public
Roadmap & Product Summary Document	[D-1-02]	Project Internal
Data Requirements Document	[D-1-03]	Project Internal
System Maturity Matrix	[D-1-04]	Project Internal
Examples of products	[D-1-05]	Project Internal
Review Procedure Document	[D-1-06]	Project Internal
Review Data Package	[D-1-07]	Project Internal
Phase 1 Review Report Document	[D-1-08]	Project Internal
Detailed Processing Model Document	[D-2-01]	Public
Round Robin Assessment Report Document	[D-2-03]	Public
Data Production Status Report	[D-3-01]	Project Internal
Final Output Dataset	[D-3-01]	Public
Product Validation Plan	[D-4-01]	Project Internal
Product Validation Report : FDR	[D-4-02a]	Public
Product Validation Report : Sea-Ice TDP	[D-4-02b]	Public
Product Validation Report: Land-Ice TDP	[D-4-02c]	Public
Product Validation Report : Ocean Waves TDP	[D-4-02d]	Public
Product Validation Report : Ocean & Coastal TDP	[D-4-02e]	Public
Product Validation Report: Inland Waters TDP	[D-4-02f]	Public
Product Validation Report: Atmosphere TDP	[D-4-02g]	Public
Uncertainty Characterization Definition Document	[D-5-01]	Project Internal
Uncertainty Characterization Report	[D-5-02]	Public
Product User Guide	[D-5-03]	Public
Completeness Report ALT	[D-7-01]	Public
Completeness Report MWR	[D-7-02]	Public

Table 2 : List of FDR4ALT deliverables

Appendix B - Acronyms

AATSR	Advanced Along-Track Scanning Radiometer
AEM	Airborne electromagnetic
AIR	AIRWAVES2
AVISO	Archivage, Validation et Interprétation des données des Satellites Océanographiques
AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System sensor
AMSU-A	Advanced Microwave Sounding Unit-A
ALT	Altimetry
ASSIST	Arctic Shipborne Sea Ice Standardization Too
ATM	Airborne Topographic Mapper
BDHI	Base de datos Hidrologica integrada
BGEP	Beaufort Gyre Exploration Project
CAL	Calibration
CCI	Climate Change Initiative
CFOSAT	Chinese-French Oceanic SATellite
CDS	Copernicus Data Service
CLS	Collecte Localisation Satellite
CMEMS	Copernicus Marine Environment Monitoring Service
CMSAF	Climate Monitoring Satellite Application Facility
CNES	Centre National des Etudes Spatiales
CRREL	Cold Regions Research and Engineering Laboratory
DAHITI	Database for Hydrological Time Series of Inland Waters
DGA	Direccion General de Aguas
ENVISAT	ENVIronment SATellite
EMD	Empirical mode decomposition
EO	Earth Observation
EPS	European Polar System
ERA	ECMWF Re-Analysis
ERS	European Remote-Sensing Satellite
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
FCDR	Fundamental Climate Data Record
FDR	Fundamental Data Records
FIDUCEO	Fidelity and uncertainty in climate data records from Earth Observations
FMR	Full Mission Reprocessing
FYI	First Year Ice
GEWEX	Global Energy and Water Exchanges
GFO	Geosat Follow-On
GIEMS	Global Inundation Extent from Multi-Satellites
GMSL	Global Mean Sea Level
GNSS	Global Navigation Satellite System
GPM	Global Precipitation Measurement
GRDC	Global Runoff Data Centre
G-REALM	Global Reservoir And Lake Monitor
G-VAP	GEWEX Water Vapour Assessment
HYBAM	HYdro-géochimie du Bassin AMazonien
ICARE	

IGM	Instituto Geografico Militar
IGN	Instituto Geografico Nacional
IMB	Ice Mass Balance
INA	Instituto Nacional de Agua
ISRO	Indian Space Research Organisation
IRPI	Istituto di Ricerca per la Protezione Idrogeologia
IWMI	International Water Management Institute
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
LIDAR	Ligth Detection And Ranging
LTAN	Local time of the ascending node
LWP	Liquid Water Path
MAC	Multisensor Advanced Climatology
MEAS-SIM	Measure-Simulation
MQE	Mean Quadratic Error
MSSH	Mean Sea Surface Height
MWR	Microwave Radiometer
NASA	National Aeronautics and Space Administration
NE	North East
NN	Neural Network
NPI	Norwegian Polar institute
NWP	Numerical Weather Prediction
NOAA	National Oceanic and Atmospheric Administration
OIB	Operation Ice Bridge
OLC	Open Loop Calibration
OSTST	Oceanography Surface Topography Science Team
POSTEL	Pôle d'Observation des Surfaces continentales par TELEdétection
PTR	Point Target Response
RD	Reference Document
REAPER	Reprocessing of Altimeter Products for ERS
RM	Review Meeting
RSS	Remote Sensing System
SALP	Service d'Altimétrie et de Localisation Précise
SARAL	Satellite with Argos and Altika
SLA	Sea Level Anomaly
SCICEX	Submarine Arctic Science Program
SGDR	Sensor Geophysical Data Record
SHOA	Servicio Hidrografico y Oceanografico de la Armada
SSB	Sea State Bias
SSH	Sea Surface Height
SSM/I	Special sensor microwave/imager
SST	Sea Surface Temperature
SWH	Significant Wave Height
SWIM	Surface Waves Investigation and Monitoring instrument
TAC	Thematic Assembly Center
TB	Température de Brillance (Brightness Temperature)
TDP	Thematic Data Products
TDS	Test Data Set
TFMRA	Threshold First-Maximum Retracker Algorithm
TMR	Topex Microwave Radiometer
TP	Topex/Poseidon

TCWV	Total column water vapour
VCC	Vicarious calibration
VS	Virtual Station
ULS	Upward Looking Sonar
USA	United States of America
USDA	United States Department of Agriculture
WHALES	Wave Height Adaptive Leading Edge Subwaveform
WTC	Wet Tropospheric Correction