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ESA Climate Change Initiative (CCI+) **Essential Climate Variable (ECV)** **Antarctica_Ice_Sheet_cci+ (AIS_cci+)**

Product Validation and Intercomparison Report (PVIR)

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Signatures page

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Change Log

Issue	Author	Affected Section	Change	Status
0.5	D. Fantin	All	Document Creation	
1.0	M. Horwath	All	Document consolidation for delivery	Delivered to ESA

Acronyms and Abbreviations

Acronym	Explanation
AIS	Antarctic Ice Sheet
ADP	Algorithm Development Plan
AIS_cci+	Antarctic Ice Sheets CCI project Extension
API	Antarctic Peninsula
ATBD	Algorithm Theoretical Basis Document
CAR	Climate Assessment Report
CCI(+)	Climate Change Initiative (Extension)
CFL	Calving Front Location
CONAE	Comisión Nacional de Actividades Espaciales
DEM	Digital Elevation Model
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DTU	Danish Technical University
EAIS	East Antarctic Ice Sheet
ECV	Essential Climate Variable
ENVEO	ENVironmental Earth Observation GmbH
EO	Earth Observation
ESA	European Space Agency
GLL	Grounding Line Location
GLM	Grounding Line Migration
GMB	Gravimetric Mass Balance
ISCL	Ice Shelf Coast Line
IV	Ice Velocity
IV-TDM	Ice Velocity Tidal Correction Module
IVC	Ice Velocity Change
MFID	Mass Flux Ice Discharge
MPC	Mission Performance Cluster
SEC	Surface Elevation Change
SL	Science Lead
SOW	Statement of Work
ST	Science & Technology AS
TOPS	Terrain Observation by Progressive Scans
TUD	Technical University of Dresden
UB	University of Bristol
UCL	University College London
UL	University of Leeds
UN	University of Northumbria
WAIS	West Antarctic Ice Sheet
NASA	National Aeronautics and Space Administration

SAR	Synthetic Aperture Radar
InSAR	Interferometric SAR
ML	Machine Learning

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1 Introduction

1.1 Purpose and Scope

This document contains the Product Validation and Intercomparison Report (PVIR) for the Antarctica_Ice_Sheet_cci (AIS_cci) project for CCI+ Phase 2, in accordance to contract and SoW [AD1 and AD2].

The AIS_cci science team has assessed the ECV products in the Climate Research Data Package. An intercomparison of the ECV products with products from other missions and other R&D initiatives has been carried out.

The PVIR describes the results of the validation and inter-comparison exercises, and quantifies the accuracy of the derived products against the validation data and comparable alternative satellite-based products generated by international projects.

The Product Validation and Inter-comparison Report gives a complete report of the activities executed to assessment of the quality of the generated ECV products and the results achieved.

1.2 Document Structure

This document comprises four parts describing each of the parameters of the AIS_cci Essential Climate Variable (ECV). Each parameter has its own chapter as seen below:

- Surface Elevation Change (SEC);
- Ice Velocity (IV);
- Grounding Line Location (GLL);
- Gravimetric Mass Balance (GMB);
- Ice Shelf Coast Line (ISCL);
- Uplift/Vertical ice velocity product.

Each parameter chapter follows a general structure including

- a description of the requirements for an independent validation data set (Sec. x.1.1)
- a description of available sources of validation data including in-situ observations and alternative data sets (e.g. available products, models, etc.) (Sec. x.1.2)
- a detailed assessment of the validation data including a description of errors and biases as well as uncertainties associated to the data (Sec. x.1.3)
- a description of the selection of validation data sets based on the outlined requirements and assessment of available data (Sec. x.1.4)
- a description of the validation procedure performed on the derived ECV products against the selected validation data sets (Sec. x.2)

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- a detailed analysis of the uncertainty of the ECV products with reference to the independent validation data (Sec. x.3)
- recommendations for fixing errors and/or improving the overall product quality (Sec. x.4)

In the interest of brevity, references are given to other project documentation when possible.

1.3 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	ESA/Contract No. 4000143397/23/I-NB CCI+ PHASE 2 - AIS	CCI+ PHASE 2 - NEW R&D ON CCI ECVS for AIS CCI	13.02.2024	NA
AD2	ESA-EOP-SC-AMT-2023-12 and its appendix 2	STATEMENT OF WORK, ESA EXPRESS PROCUREMENT – EXPRO CCI+ Phase 2 – Theme II – Antarctic Ice Sheet (AIS)	14.07.2023	1.2

Note: If not provided, the reference applies to the latest released Issue/Revision/Version

Table 1.2: List of Reference Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
RD1	ST-UL-ESA-AISCCI-PVIR-001	Product Validation and Intercomparison Report (PVIR) (AIS CCI)	10.03.2018	1.3
RD2	ST-UL-ESA-AISCCI+-PVIR-001	Product Validation and Intercomparison Report (PVIR) (AIS CCI+ Phase 1)	01.10.2021	1.0

Note: If not provided, the reference applies to the latest released Issue/Revision/Version

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2 Surface Elevation Change (SEC)

This chapter gives a complete report of the activities carried out to assess the quality of the SEC products.

2.1 Independent validation data

2.1.1 Requirements

The data sets used to validate the Surface Elevation Change (SEC) product must have been acquired in Antarctica, be freely available for the project to use, must overlap either fully or partly with the satellite radar altimetry time series used to produce the SEC product, and must be able to be used to measure surface elevation change.

2.1.2 Sources

Airborne Topographic Mapper (ATM) airborne elevation data has been collected in Antarctica on numerous Operation IceBridge campaigns between 1993 and 2019. The validating dataset is the level 4 product, ATM L4 Surface Elevation Rate of Change V001 (Studinger, 2014). This can be obtained free of charge on registration, from <https://icebridge.gsfc.nasa.gov/>. The surface elevation rate of change in this dataset is calculated from the change in elevations recorded at the same location between two overflights.

2.1.3 Assessment

The airborne validation data sets are produced from data acquired by laser altimeter, therefore it is anticipated that there may be some bias in the validation results because the laser altimeters reflect off the ice surface, whereas the satellite radar altimeters penetrate some depth into the snowpack.

ASIRAS is an airborne radar altimetry instrument that operates at 13.5GHz, the same central frequency as CryoSat-2. This dataset is likely to be subject to similar penetration effects as the satellite radar altimetry data used to produce the SEC product. The level 4 SEC product allows direct comparison of surface elevation change between separate instruments.

It should be noted that the CCI SEC product is calculated over a long, continuous, multiple-mission period, whereas the ASIRAS dataset is acquired during various shorter periods within the limits of the CCI SEC product time periods.

2.1.4 Selection

All available validation data acquired in Antarctica was used to validate the Antarctic CCI SEC product. The data sets used were acquired from 2002 to 2016, which coincides with the Envisat and CryoSat-2 missions. Geographically, most Operation IceBridge campaigns were flown over West Antarctica and the Antarctic Peninsula. Only measurements taken over land were used.

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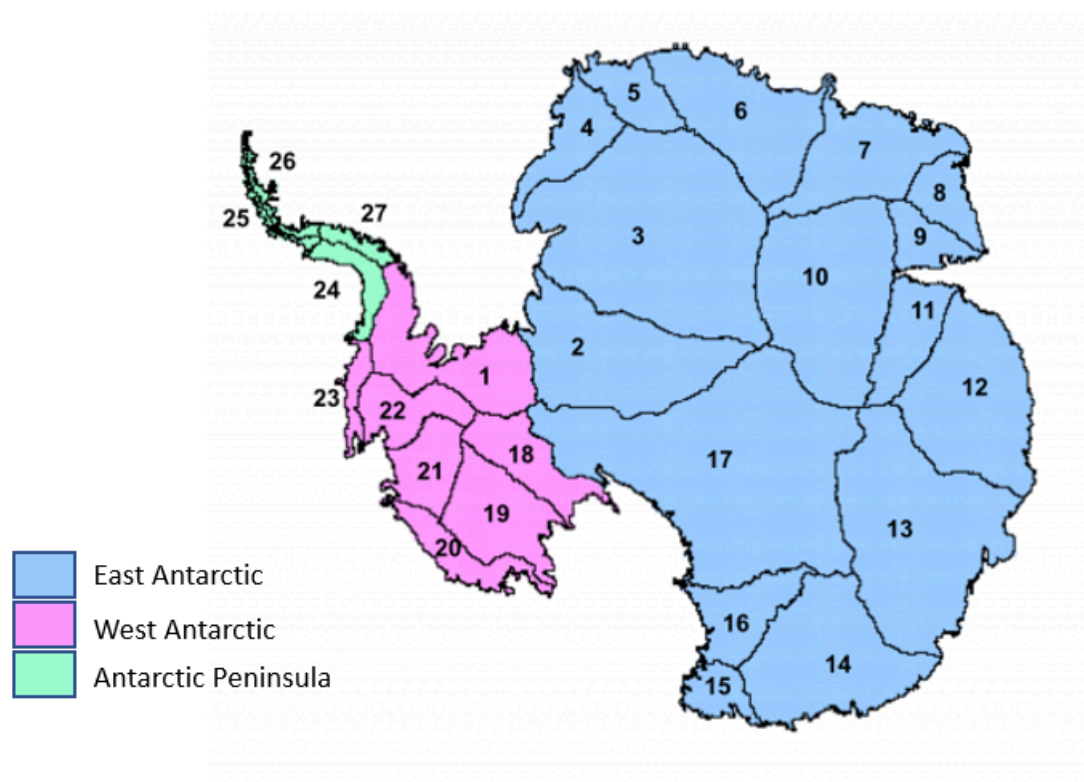


Figure 2-1: Map showing the geographic regions and drainage basins of Antarctica, used during validation of the Antarctic cci surface elevation change product. Drainage basins are based on the Zwally definitions (Zwally et al., 2012). Credit: IMBIE

2.2 Validation procedure

The validation method is a comparison of CCI SEC results with all ASIRAS measurements from the validating dataset that coincide in time and space. This is not a direct comparison to the product dataset, as the ASIRAS overflights are highly irregular. Instead we use the underlying elevation change timeseries and analysis methods from which the CCI SEC dataset was derived to produce results comparable to ASIRAS.

The CCI SEC product is calculated from modelling based on 5km by 5km grid cells in which we derive a series of elevation change values (dh) over time. We can apply a linear least-squares fit over any time period to the dh timeseries in a cell to derive the rate of change of surface elevation, ie dh/dt . For validation we apply the same time periods as ASIRAS to the grid cell timeseries in which ASIRAS took a measurement. We averaged the rates of elevation change computed from pairs of ASIRAS overflights in each cell to match the spatial resolution of the satellite data. The comparison was restricted to where the root mean square of the ASIRAS results and the standard deviation of the CCI SEC results was less than or equal to 0.4 m/year, and the time

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period between ASIRAS overflights was at least 2 years. The difference was calculated as CCI SEC minus ASIRAS.

The airborne data is sampled at 250m spatial resolution along flight-lines that preferentially sample fast-thinning ice. Because of this, its measurements tend to be biased to a higher value when compared to coarsely gridded data (Flament and Remy 2012, McMillan 2014). To take account of this, a bias factor is estimated using a high-resolution (1km by 1km) map of ice velocity from BISICLES (Berkeley Ice Sheet Initiative for Climate at Extreme Scales) (Cornford, 2013). This bias factor is the velocity of the 1km by 1km grid cell containing the ASIRAS measurement with respect to the average velocity of the 5km by 5km CCI SEC cell containing it, averaged over all measurements used.

Operation IceBridge ended following the launch of ICESat-2, resulting in no airborne laser altimetry observations being available to validate the CCI time series after autumn 2019. Instead, since CryoSat-2 and ICESat-2 collect measurements at the same time, it is possible to compare time-series of elevation changes from these independent satellite sensors to ensure the consistency and quality of the CCI surface elevation time-series. We compare the CCI SEC products derived from CryoSat-2 (CS2) and ICESat-2 (IS2) on the same 5 km by 5 km grid during the period they overlap (2018-2025). We compare (1) surface elevation change rates derived from both missions at the individual grid cell level across the entire Antarctic continent and (2) the average surface elevation change rates across the 27 different drainage basins of Antarctica derived from the elevation change time series to assess the agreement between the independent satellite radar and laser altimetry datasets.

The terrain in each drainage basin varies. The CCI SEC product is expected to perform at its best over ice sheets, ie regions of low slope. However, the available comparison data covered many terrains. A comparison covering the whole region was made, as well as separate comparisons for each drainage basin, although it should be noted that the number of datapoints in each basin varies greatly.

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2.3 Validation outcome

2.3.1 SEC Validation against airborne laser altimetry (2002-2019)

The differences between the CCI SEC and ASIRAS results over the Antarctic as a whole are shown at the grid cell level in Figure 2-2, below.

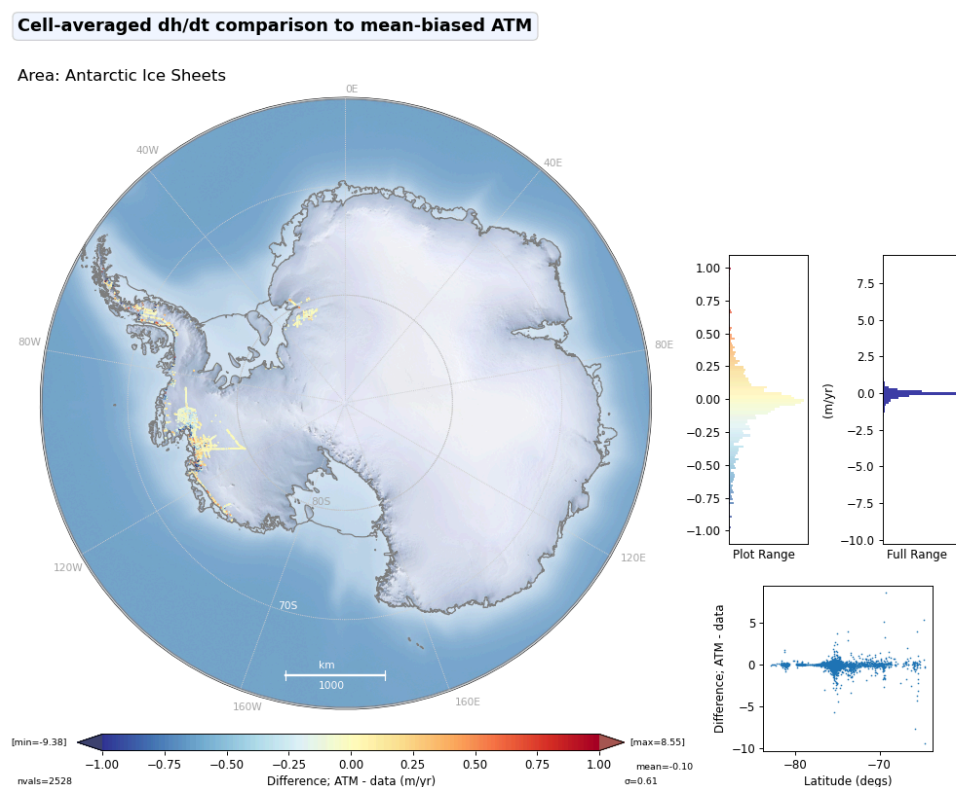


Figure 2-2: Comparison of CCI SEC and ASIRAS surface elevation change rates, using all selected data.

The results of the whole-region comparison are shown as a histogram and scatter plot in Figure 2-3 below.

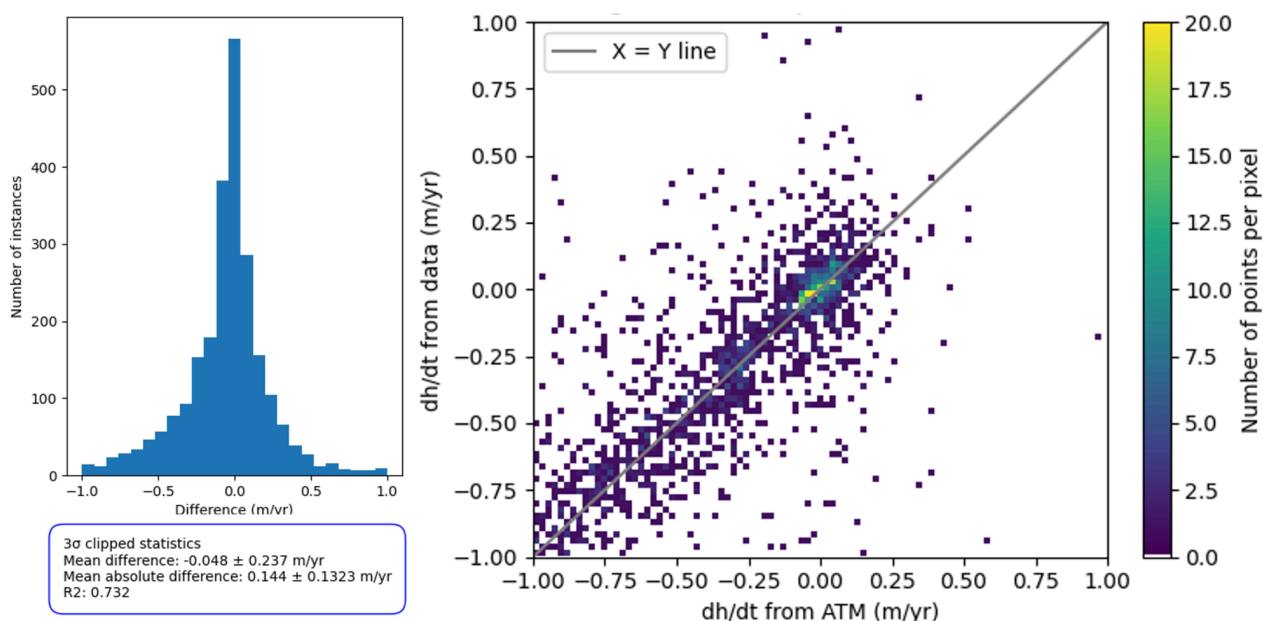


Figure 2-3: Histogram (left) and scatter plot (right) showing the distribution of differences between the satellite surface elevation change from the CCI SEC product, and the ASIRAS surface elevation change.

Statistics on the difference in change, CCI SEC minus ASIRAS, are compiled. Comparison statistics are calculated from a restricted dataset which excludes outliers by only considering data points within ± 3 standard deviations from the mean of the whole, original dataset.

The statistics for the dataset as a whole are:

- Absolute mean difference: 14 cm/yr
- Absolute standard deviation of difference: 13 cm/yr
- Coefficient of determination, R^2 : 0.73
- Mean slope of cells considered: 0.89°
- Number of cells considered: 2536
- Number of datapoints in total considered: 197463

Statistics on the difference in change, CCI SEC minus ASIRAS, for each basin considered separately are tabulated below. The number of cells used in each basin is noted as the SEC products were only compared when a result existed for both datasets. The mean slope of the cells used in each basin is also noted, as a measure of its terrain variability.

Table 2-1: Table, showing statistics of the difference between the CCI SEC and ASIRAS datasets for all validation basins. WA = West Antarctica, EA = East Antarctica, AP = Antarctic peninsula. Figures rounded to two decimal places.

	Absolute mean (cm/yr)	Absolute standard deviation (cm/yr)	R2, coefficient of determination	Number of cells considered
WA, basin 1	4	3	0.43	30
EA, basin 2	6	3	0.32	6
EA, basin 3	6	5	0.01	212
WA, basin 19	2	1	0.66	40
WA, basin 20	21	16	0.77	184
WA, basin 21	14	14	0.79	753
WA, basin 22	16	13	0.77	709
WA, basin 23	25	21	0.41	120
AP, basin 24	17	17	0.07	270
AP, basin 25	26	23	0.55	69
AP, basin 26	20	17	0.07	105
AP, basin 27	10	8	0.01	38

Histograms of the separate basin comparisons are shown in Figure 2-4 below.

Cell-averaged dh/dt comparison to basin-mean-biased ATM. Difference; ATM - data

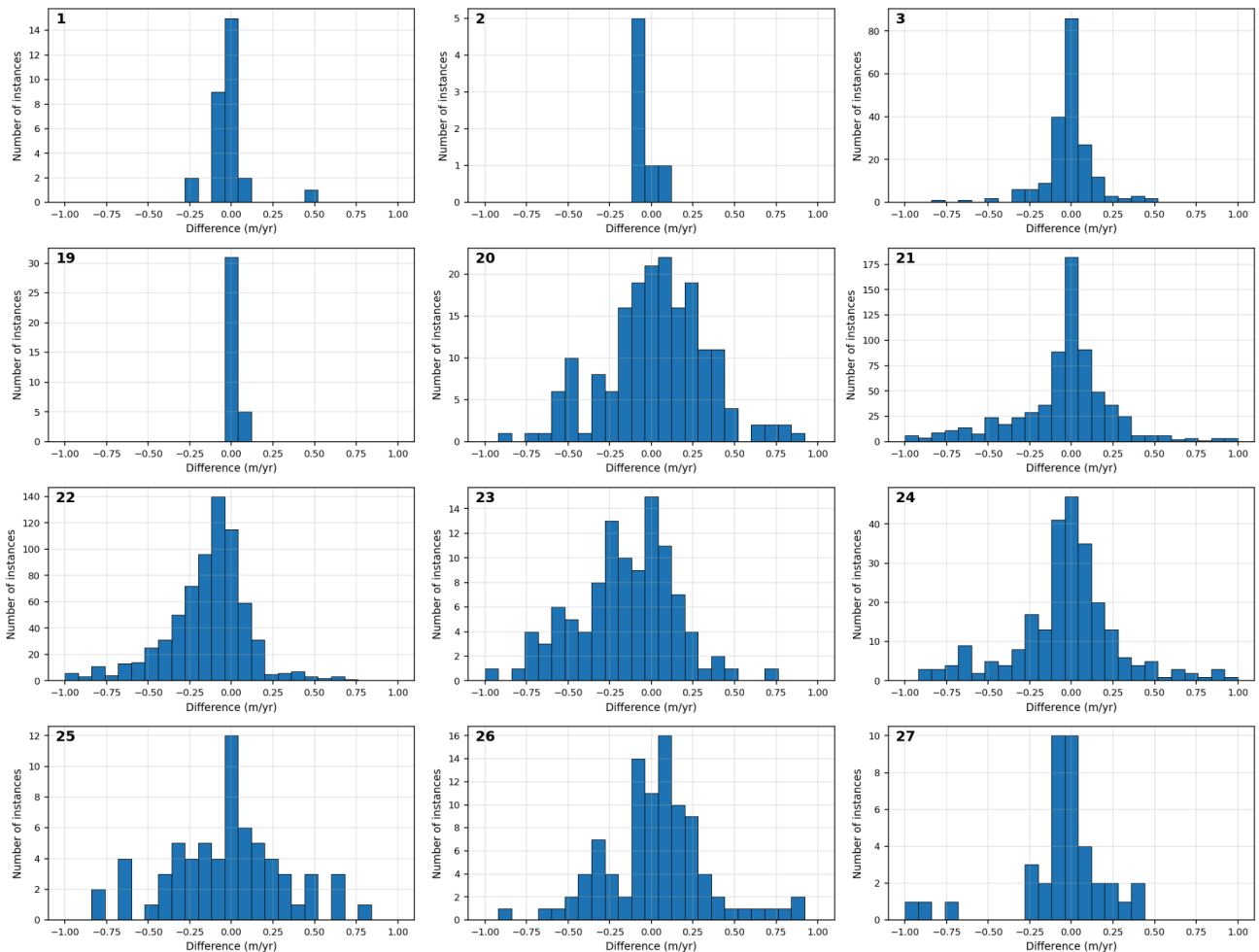


Figure 2-4: Histograms of CCI SEC and ASIRAS surface elevation change differences, for separate basins (basin number top left in each case).

In summary, these results show that the mean difference between the validation dataset and the SEC product is less than 30 centimetres per year in all areas, although the correlation between signals is poor in the poorly sampled and highly sloping basins, with the lowest of the well-correlated differences generally occurring in West Antarctica. We attribute the larger difference between the validation data and the SEC product on the Antarctic Peninsula, in comparison to West Antarctica, to the more steeply sloping topography which is known to be more challenging terrain for the altimeter data retrieval to operate in.

2.3.2 CryoSat-2 and ICESat-2 SEC Inter-comparison

The differences between the CryoSat-2 and ICESat-2 products over the Antarctic and calculated over the same time period (2018-2025) are shown at the grid cell level in Figure 2-5, below.

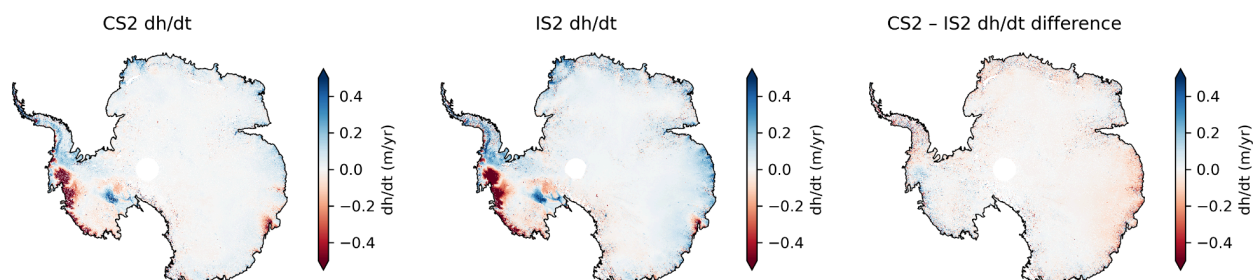


Figure 2-5: Maps of SEC between 2018 and 2025 from (left) CryoSat-2, (middle) ICESat-2 and (right) their difference.

The results of the whole-ice sheet comparison are shown as a histogram in Figure 2-6, below.

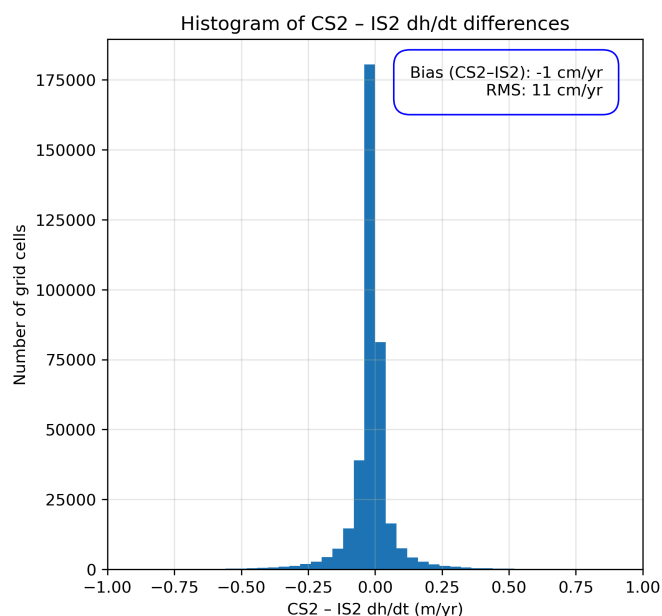


Figure 2-6: Histogram showing the distribution of differences between the satellite surface elevation change from the CCI CryoSat-2 and ICESat-2 SEC products.

The statistics for the dataset as a whole are:

- Mean difference (CryoSat-2 minus ICESat-2): -1 cm/yr
- Root mean square difference: 11 cm/yr.

A comparison of basin-mean surface elevation change rates derived from CryoSat-2 and ICESat-2 is presented in Figure 2-7 below:

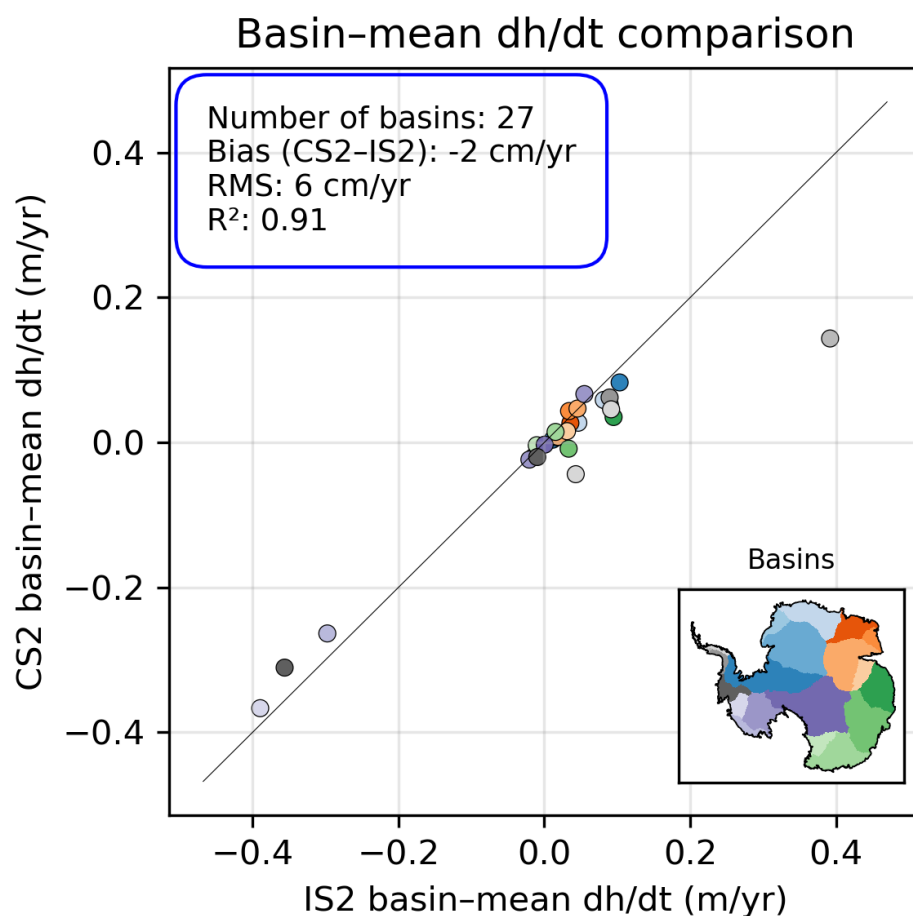


Figure 2-7: Histogram showing the distribution of differences between the satellite surface elevation change from the CCI CryoSat-2 and ICESat-2 SEC products.

Figure 2-7 demonstrates strong agreement between the two datasets, with most basins clustering tightly along the 1:1 line. The high R² value of 0.91 indicates excellent correlation between CS2 and IS2 basin-mean dh/dt estimates. Basin-mean surface elevation change rates derived from the two missions agree to within a root mean square difference of 6 cm/yr, indicating excellent agreement. The largest discrepancies are found at the northern tip of the Peninsula where the terrain is steeply sloping, consistent with our comparison to ASIRAS.

2.4 Acknowledgement of the data contributor for SEC validation

The following dataset was used for the Operation IceBridge airborne laser altimeter validation:

Studinger, M. S. 2014, updated 2016. IceBridge ATM L4 Surface Elevation rate of Change, Version 1, Antarctica subset. Boulder, Colorado, USA. NASA National Snow and Ice Data Center Distributed Active Archive Centre. Doi:<http://dx.doi.org/10.5067/BCW6CI3TXOCY>. Accessed 25th May 2017.

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The CryoSat-2 and ICESat-2 intercomparison was performed using the latest version of the AIS CCI+ products available at the time of writing (AIS CCI+ v2, Nov 2025).

The ICESat-2 surface elevation change rates were produced using the ATL06 v006 data:

Smith, B., Adusumilli, S., Csathó, B. M., Felikson, D., Fricker, H. A., Gardner, A. S., Holschuh, N., Lee, J., Nilsson, J., Paolo, F., Siegfried, M. R., Sutterley, T. & the ICESat-2 Science Team. (2023). ATLAS/ICESat-2 L3A Land Ice Height (ATL06, Version 6). [Data Set]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. <https://doi.org/10.5067/ATLAS/ATL06.006>.

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3 Ice Velocity (IV)

This chapter describes the activities undertaken to assess the quality of the ice velocity (IV) products generated within AIS CCI+ phase 2. The intercomparison/validation activities focus on Antarctic IV mosaics derived from Sentinel-1 (S1) SAR data acquired between September 2020 and December 2024 (Figure 3-1). These and earlier IV products form the main input for the derived products on ice velocity change and ice discharge (Option-3). The activities presented here complement previous validation efforts carried out during earlier phases of the project, which included intercomparisons of monthly, annual and multi-annual ice sheet wide composite mosaics as well as individual tracks velocity maps based on 6 to 12-day repeat image pairs with in-situ GPS measurements, published external velocity datasets, and data from other high-resolution SAR sensors (e.g. TerraSAR-X). Additional quality-assessment (QA) tests—such as analyses of IV over stable terrain—were also performed, with results documented in [RD1] and [RD2]. In this chapter, we extend these intercomparison and QA activities to newly generated datasets, including updated stable-terrain analyses and intercomparisons with external annual ice velocity maps.

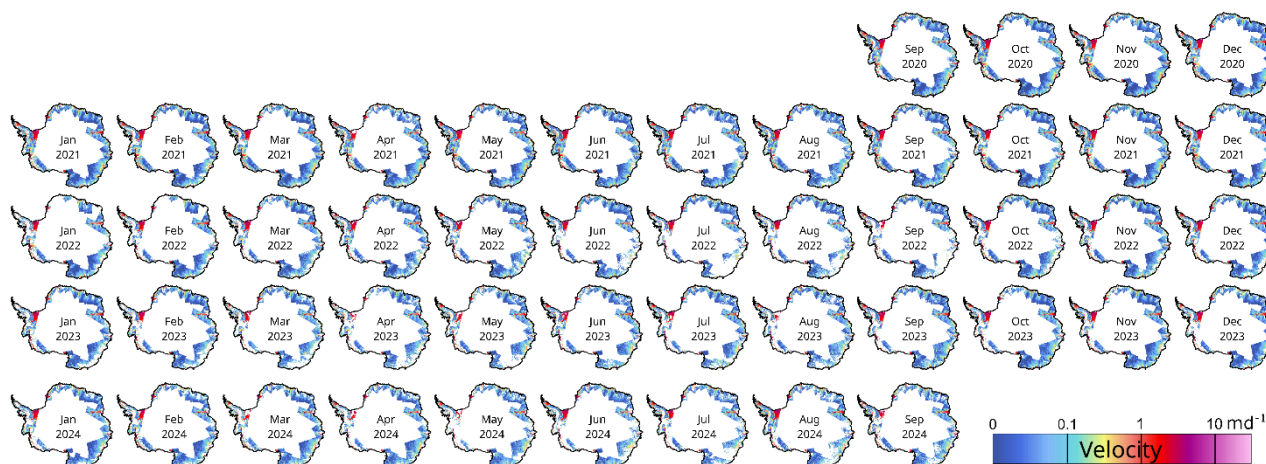


Figure 3-1: Monthly IV mosaics of the Antarctic coastal margin for the period Sept 2020 till December 2024 derived from Copernicus Sentinel-1.

3.1 Validation data

Due to the limited availability of in-situ GPS data for the period covered by the Antarctic Ice Sheet CCI+ products (2020–2024), the validation activities are restricted to intercomparisons with ice-velocity maps from overlapping time periods and the stable-terrain test.

External Ice Velocity Map: As part of the Inter-Mission Time Series of Land Ice Velocity and Elevation (ITS_LIVE) project, within NASA’s Making Earth System Data Records for Use in Research Environments (MEaSUREs) Program, annual Antarctic IV maps have been generated from multi-sensor SAR data and optical imagery. These maps are freely available in NetCDF format and currently released as Version 2.0 (Gardner et al., 2025). The ITS_LIVE Version 2.0 velocity products are processed at 120 m resolution and combine data from Sentinel-1 and Sentinel-2 with optical imagery from Landsat-8. Here we use the latest available annual maps covering the years 2021 and 2022 (Fig 3-2).

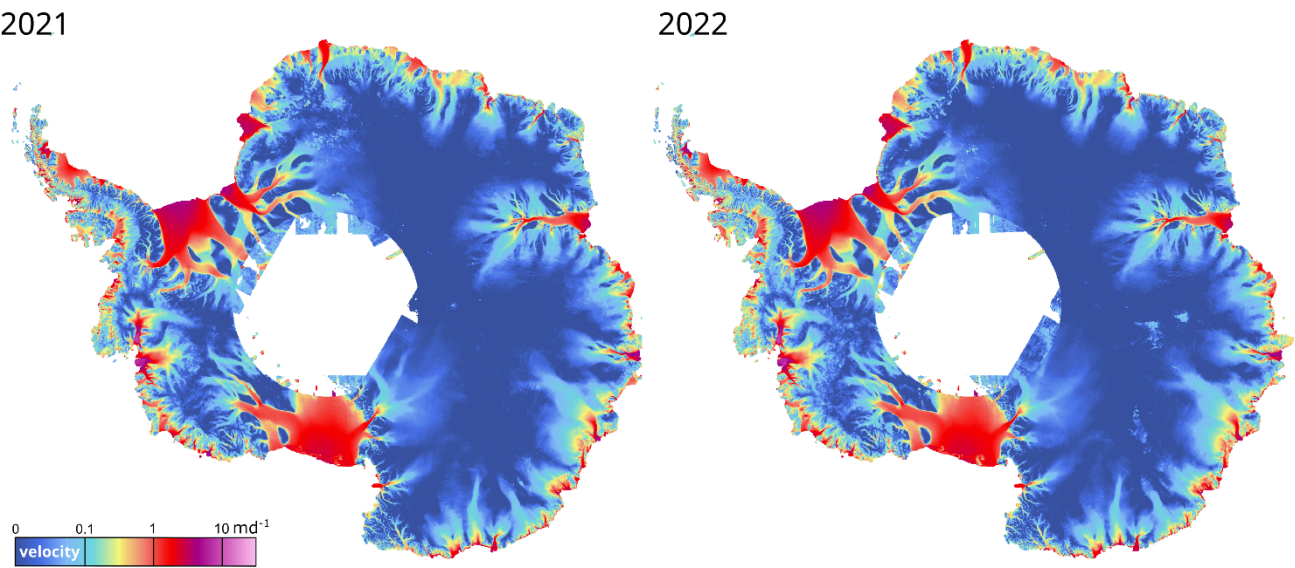


Figure 3-2: ITS_LIVE ice velocity maps for Antarctica in 2021 and 2022 (Gardner et al., 2025).

Rock Outcrop Map: For the stable terrain test we use a rock outline shapefile derived from Landsat-8 Operational Land Imager (OLI) multispectral images (Figure 3-3; Burton-Johnson et al., 2016). The dataset is generated using an automated methodology for snow and rock differentiation that excludes areas of snow (both illuminated and shaded), clouds and liquid water whilst identifying both sunlit and shaded rock. Compared with conventional approaches—such as thresholds applied to the Normalized Difference Snow Index (NDSI)—this methodology provides higher classification accuracy and improved spatial consistency. The source images were acquired in austral summers between October 2013 and March 2015. The dataset is provided as a supplement with the paper (Burton-Johnson et al., 2016).

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Figure 3-3: Map of Antarctica showing in blue floating ice shelves and in red the rock outcrop shapefile used for the stable terrain test (Burton-Johnson et al., 2016).

3.2 Validation procedure

For the quality assessment (QA) of IV products a series of standard tests/measures were developed providing various levels of validation [RD2]. Here we apply two of these:

- 1) The products are evaluated against publicly available ice-velocity datasets covering the same region. Although these external products may differ in temporal coverage, spatial resolution, or sensor composition, they provide an independent benchmark for quality assurance, especially in areas where only minimal dynamical change is expected. For this assessment, we use the most recent multi-sensor annual velocity maps from ITS_LIVE for 2020 and 2021 (Gardner et al., 2025) to intercompare with the corresponding Sentinel-1 annual mosaics. For the intercomparison, the reference dataset is resampled to match the grid spacing, projection, and spatial extent of the AIS CCI+ Sentinel-1 product. Only overlapping pixels are retained for the point-by-point comparison. Apparent velocity differences greater than 1 m d^{-1} are excluded from the statistical analysis to limit the influence of outliers. It should be noted that the ITS_LIVE annual composites span January to December, whereas the S1-derived annual IV maps cover April to March (aligned with the glaciological year). Consequently, some differences between the products may arise from the mismatch in temporal coverage. The computed quality metrics include the mean and root-mean-square error (RMSE) of the differences in the eastward (E) and northward (N) velocity components.
- 2) The products are also evaluated by analyzing the apparent velocity over stable, ice-free terrain where no motion is expected. This assessment provides an effective measure of any systematic bias introduced by the end-to-end processing chain, including image co-registration and velocity retrieval. Ice-covered (moving) and ice-free (stable) regions are separated using a rock-outcrop polygon dataset

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(Burton-Johnson et al., 2016). Prior to extracting stable-ground pixels for statistical analysis, buffer zones are applied around the polygons to reduce contamination from misclassified areas; alternatively, a final visual inspection is performed to identify and remove any remaining misclassified terrain. The stable-terrain test is conducted for all generated monthly maps (Sept 2020–Dec 2024), under the assumption that ice-free areas remain static over this period. The resulting quality metrics include the mean and root-mean-square deviation (RMSD) of the apparent velocity over stable terrain, where mean values are expected to be close to zero.

3.3 Validation outcome

We present difference histograms and spatial difference maps for both the easting and northing velocity components (Figure 3-4), along with summary statistics for the 2021 and 2022 datasets (Table 3-1). These figures and metrics illustrate the performance and consistency between the IV products. The intercomparison between the S1 IV mosaics and the MEaSUREs ITS_LIVE datasets shows a mean difference of 0.00 m d⁻¹ (RMSE: 0.05–0.07 m d⁻¹) for both components across both annual maps, indicating excellent agreement. Larger discrepancies are confined to a few localized regions—such as Pine Island Glacier and the Stancomb-Wills Ice Tongue—which might reflect genuine temporal changes (arising from the slight mismatch in temporal coverage) or differences arising from processing parameters (e.g., window sizes) that influence the representation of high-shear glacier margins.

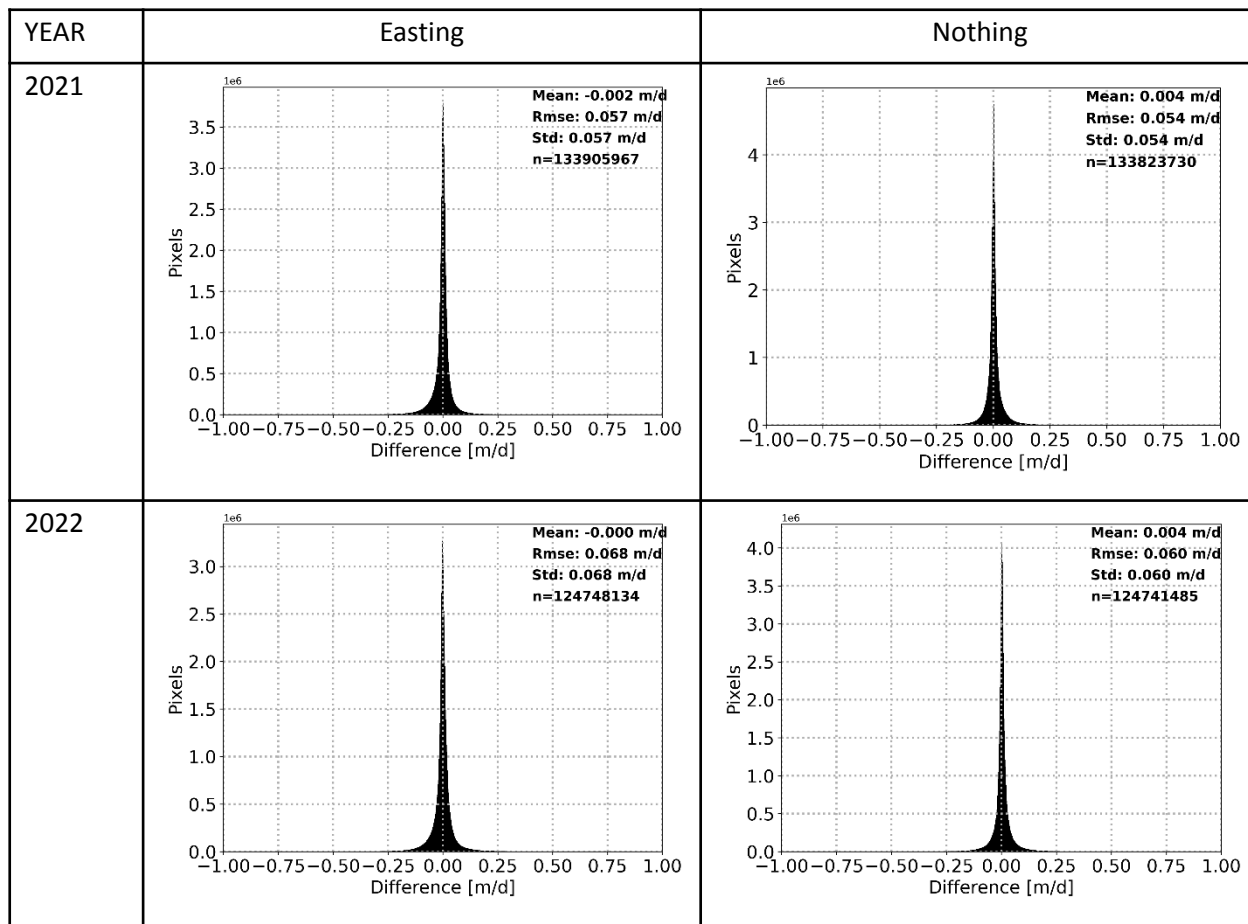


Figure 3-4: Difference histograms for easting (left) and northing (right) component for the pixel-wise intercomparison between the ENVEO Sentinel-1 ice sheet annual velocity maps 2020/21 and 2021/22 and the MEaSUREs annual velocity maps for 2020 and 2021 (Gardner et al., 2025).

Table 3-1: Summary of IV comparison quality assessment.

Product Analysed	Reference dataset Measures	Number of pixels used in analysis	Mean difference Easting [m d-1]	RMSE difference Easting [m d-1]	Mean difference Northing [m d-1]	RMSE difference Northing [m d-1]
S1 Ice Velocity map 2020/21	ITS_LIVE_velocity_120m_R GI19A_2021_v02	~134 M	-0.00	0.06	0.00	0.05
S1 Ice Velocity map 2021/22	ITS_LIVE_velocity_120m_R GI19A_2022_v02	~125 M	0.00	0.07	0.00	0.06

The stable-ground test is performed for all monthly IV maps. The red regions in Figure 3-3 indicate the stable, ice-free areas used in the analysis. Example histograms for January 2024 are shown in Figure 3-5, illustrating the distribution of the easting and northing velocity components; for stable terrain, these distributions should ideally be centered around zero. Deviations from zero can arise from several sources, including inaccuracies in the rock-outcrop shapefile, imperfections in the layover mask, or artifacts introduced by the velocity-retrieval algorithm. A summary of the stable-ground test results is provided in Table 3-2. The analysis

yields mean values of -0.001 m d^{-1} in the easting component and 0.002 m d^{-1} in the northing component, with corresponding mean RMSE values of 0.022 m d^{-1} and 0.020 m d^{-1} , respectively.

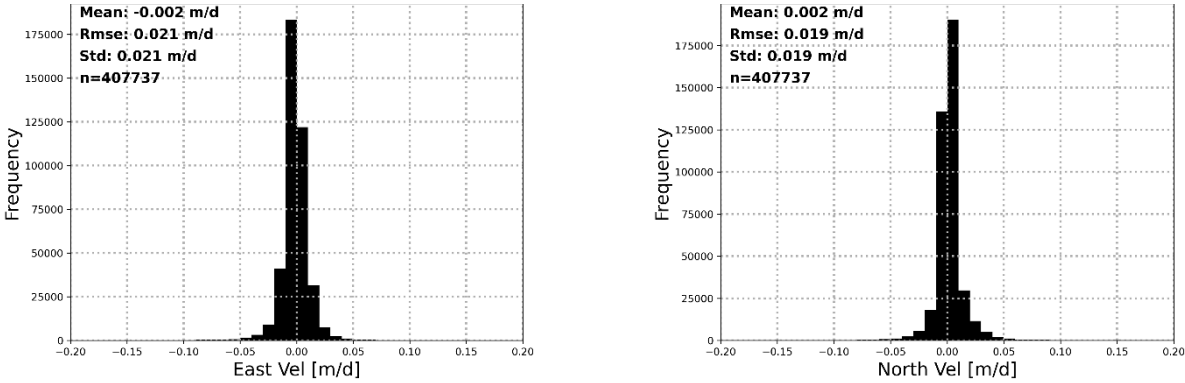


Figure 3-5: Histogram of easting (left) and northing (right) velocity on stable terrain for January 2024.

Table 3-2: Summary of stable rock quality assessment for averaged S1 ice velocity map (Sept 2020 - Dec 2024).

Year	Month	# pixels	Mean E [m d^{-1}]	RMSE E [m d^{-1}]	Mean N [m d^{-1}]	RMSE N [m d^{-1}]
2020	Sept	419474	-0,001	0,020	0,001	0,018
	Oct	419501	-0,001	0,021	0,002	0,019
	Nov	419410	-0,001	0,021	0,002	0,019
	Dec	419394	-0,002	0,021	0,001	0,019
2021	Jan	419453	0,000	0,021	0,001	0,017
	Feb	419492	-0,002	0,021	0,001	0,018
	Mar	419529	0,000	0,024	0,002	0,021
	Apr	419485	-0,002	0,022	0,001	0,019
	May	413838	-0,002	0,020	0,002	0,019
	Jun	413902	-0,001	0,019	0,001	0,017
	Jul	413840	0,000	0,019	0,001	0,017
	Aug	419526	-0,001	0,019	0,002	0,017
	Sept	419449	-0,002	0,020	0,001	0,018
	Oct	419486	-0,001	0,021	0,002	0,018
	Nov	419415	0,000	0,021	0,002	0,019
	Dec	419381	-0,003	0,022	0,001	0,022
2022	Jan	372498	-0,001	0,021	0,003	0,018
	Feb	372533	-0,001	0,022	0,002	0,019
	Mar	413936	-0,001	0,022	0,002	0,019
	Apr	411015	-0,001	0,021	0,002	0,019
	May	410965	-0,001	0,021	0,002	0,019
	Jun	410915	-0,002	0,022	0,001	0,019

	Jul	410056	-0,001	0,021	0,002	0,020
	Aug	411040	-0,001	0,020	0,001	0,017
	Sept	411060	-0,002	0,021	0,001	0,018
	Oct	410981	-0,001	0,020	0,002	0,018
	Nov	410928	-0,001	0,020	0,002	0,020
	Dec	410966	-0,002	0,019	0,002	0,019
2023	Jan	410290	-0,001	0,019	0,002	0,017
	Feb	410940	-0,001	0,026	0,001	0,020
	Mar	410991	-0,002	0,027	0,001	0,021
	Apr	410994	-0,002	0,026	0,001	0,021
	May	411055	-0,001	0,024	0,001	0,020
	Jun	411620	-0,001	0,020	0,002	0,020
	Jul	411937	0,000	0,020	0,002	0,020
	Aug	413990	-0,002	0,019	0,002	0,020
	Sept	414004	0,002	0,026	0,002	0,031
	Oct	411924	-0,004	0,027	0,002	0,036
	Nov	411926	-0,001	0,021	0,002	0,020
	Dec	411888	-0,003	0,020	0,002	0,020
2024	Jan	407737	-0,002	0,021	0,002	0,019
	Feb	411321	-0,001	0,024	0,002	0,022
	Mar	411938	-0,002	0,029	0,002	0,022
	Apr	411950	0,002	0,029	0,003	0,025
	May	411918	-0,003	0,024	0,000	0,024
	Jun	411581	-0,002	0,020	0,001	0,018
	Jul	411599	-0,002	0,021	0,002	0,019
	Aug	411919	0,000	0,023	0,002	0,021
	Sept	411928	0,000	0,026	0,001	0,021
	Oct	411929	0,000	0,025	0,001	0,019
	Nov	411920	-0,001	0,026	0,002	0,023
	Dec	411898	-0,002	0,022	0,001	0,023
MEAN	Sep '20 - Dec '24	412128	-0,001	0,022	0,002	0,020

3.4 Acknowledgements of data contributors for IV validation

The following datasets were used for the present validation: NASA MEaSUREs ITS_LIVE, Antarctic Ice Velocity 2021 and 2022: Gardner, A. S., Fahnestock, M., Greene, C. A., Kennedy, J. H., Liukis, M., López, L. A. & Scambos, T. (2025). MEaSUREs ITS_LIVE Regional Glacier and Ice Sheet Surface Velocities. (NSIDC-0776, Version 2). Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. <https://doi.org/10.5067/JQ6337239C96>. Date Accessed 11-19-2025.

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Burton-Johnson et al, Antarctic rock outcrops shapefile: Burton-Johnson, A., Black, M., Fretwell, P. T., and Kaluza-Gilbert, J.: An automated methodology for differentiating rock from snow, clouds and sea in Antarctica from Landsat 8 imagery: a new rock outcrop map and area estimation for the entire Antarctic continent, The Cryosphere, 10, 1665–1677, <https://doi.org/10.5194/tc-10-1665-2016>, 2016.

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4 Grounding Line Location (GLL)

This chapter gives an update of the activities carried out to assess the quality of the GLL products.

4.1 Independent validation data

4.1.1 Requirements

The boundary of the grounded ice sheet includes a variety of structural conditions:

- Glacier tongues (ice thickness gradually decreases)
- Ice cliffs (ice breaks off and falls onto the ground or sea ice)
- Ice shelves (ice flows into the ocean and remains attached to the grounded ice until it calves). This is the dominant situation in Antarctica, stretching about 19,000 km in length (British Antarctic Survey, 2005).

For most cases, e.g. an outlet glacier with a floating tongue or on an ice shelf, the GLL is not directly observable. Therefore, the validation of the GLL outcome is the same as in the AIS_cci project phase 2015 – 2018 when it was carried out against similar products consisting of indirectly derived GLLs from a variety of satellite data and the appropriate indirect method.

Although within AIS_cci we do not aim at deriving the GLL on a continental scale we selected the most commonly used Antarctica-wide GLL databases available for download at NSIDC for validation. A detailed description is given in Section 4.1.2.

In order to facilitate the intercomparison of the various GLLs, the AIS_cci GLL product is annotated with time stamps and ocean tide level differences. Since this information is not given for the validation datasets an interpretation of the comparison must be done with care in particular with respect to short term tide induced GLL migration. Therefore, we limit our comparison to a purely geometrical/spatial approach which does not take ocean tide changes into account. Only the comparison with interferometric GLLs derived from the same SAR data have a reduced tidal effect.

With the introduction of a new machine learning-based grounding line delineation we now also validate the performance of this delineation against manual delineations from the original AIS_cci GLL product.

4.1.2 Sources

Three comprehensive data sets were used to validate the AIS_cci GLL. Their details are given below.

- (1) The Antarctic grounding line derived from the MODIS Mosaic of Antarctica (**MOA**) from (Scambos et al., 2007)

This GLL was generated together with the coastline from the digital image mosaic of surface morphology assembled from 260 Moderate-resolution Imaging Spectroradiometer (MODIS) images acquired between Nov. 2003 and Feb. 2004. The good geolocation and slope sensitivity of the MOA surface morphology image made a continent-wide mapping of the coastline and the grounding line possible. In (Scambos et al., 2007) the grounding line is defined as the coastal slope break between floating and grounded ice (l_g in Figure). The

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GLL was manually digitized by following the seaward-most continuous slope break on the surface inside of (or equal to) the permanent coastline in images of the MOA surface morphology dataset.

The coastline and the grounding line are two vector files which can be downloaded at <https://earth.gsfc.nasa.gov/cryo/data/polar-altimetry/antarctic-and-greenland-drainage-systems> in various formats. The spatial resolution is 250 m. The location precision is estimated to be no worse than ± 250 m. The MOA grounding line is the only available dataset which has a 100% complete coverage including continent and islands. The time stamp (date/time) of the MODIS acquisitions used to generate the MOA grounding line segments is unfortunately not given.

(2) The Antarctic Surface Accumulation and Ice Discharge (**ASAI**D) IPY project, from (Bindshadler et al., 2011)

Two ice-dynamic features were mapped within this project: the seaward boundary of surface morphology associated with grounded ice (I_b in Figure) and the landward boundary of freely floating ice shelves or hydrostatic line (H in Figure). The boundaries were generated at a spatial resolution of 15 m from Landsat-7 imagery acquired between 1999 and 2003 and ICESat/GLAS laser altimetry from two observation periods in 2003 and 2008. The photoclinometry procedure is based on the relationship between the pixel brightness in the optical image and the surface slope. In addition an ICESat/GLAS elevation (up-sun and down-sun) is required in order to delimitate the subimage where the brightness-slope relationship is applied. The authors mention that identifying where the fast-moving glaciers discharge into ice shelves was the most challenging task. In these cases, additional MOA imagery is analysed and at all locations where the MODIS shows additional grounded ice features it will be compared to Landsat. Here the ASAI D GLL follows the MOA GLL.

The grounding line and hydrostatic line locations can be downloaded at <https://nsidc.org/data/nsidc-0489/versions/1>. The spatial resolution is 15 m. The positional accuracies of the ASAI D GLL vary from ± 52 m for the land and open ocean terminating segments to ± 502 m for the outlet glaciers. The hydrostatic line (H) is positioned with errors of over 2 km. The ASAI D GLL is consistent around the continent, but covers only 3 islands. The time stamp (date/time) of the Landsat-7 acquisitions used to generate the ASAI D GLL segments is not given.

(3) The **MEaSUREs** InSAR grounding lines from (Rignot et al., 2011b)

This GLL product consists of the mapped upper limit of tidal flexure (F in Figure) observed in differential interferograms (DInSAR) around Antarctica. The satellite data used initially are ERS-1/2 from 1992, 1994 and 1996, RSat-1 from 2000, RSat-2 from 2009 and ALOS PALSAR from 2007-2008 extending over a large time span for more than 15 years. Meanwhile the MEaSUREs product has been completed with new GLLs derived from recent Sentinel-1 and COSMO SkyMed data. The DInSAR technique to obtain the distinct signature of elastic bending is the same as that used in the present AIS_cci project. The GLL was manually mapped in the SAR geometry and georeferenced afterwards.

The grounding line can be downloaded at <https://nsidc.org/data/nsidc-0498> in the currently available Version 2.0 (Rignot et al., 2017). The spatial resolution is 50 m. The standard deviation of the errors is ± 100 m

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and was found from comparison with multiple mappings, instruments, and epochs (including the MOA grounding line). Locally, greater variations are observed. In some cases, km-wide migrations were detected.

The coverage is incomplete in some areas (due to the lack of coherence) while in other areas multiple inner flexure lines (F) were obtained at different dates. As time stamps only the date of the SAR acquisitions used to generate the MEaSURES GLL segments, and the satellite orbit are annotated in the product which makes the extraction of ocean tide levels needed for comparison very laborious. Although an update of the MEaSURES GLL product annotated with exact date/time stamps is expected this did not occur at this date and this limits the possibilities to extend the ocean tide level dependent validation to other areas.

- (4) The Machine Learning delineated GLL from Sentinel-1 A/B data of 2018 from (Mohajerani et al., 2021)

According to the authors this represents a complete grounding line delineation around the Antarctic Ice Sheet in the year 2018. The SAR data used are Sentinel-1 A/B with 6 and 12 days repeat pass. Besides the timely limited dataset, the difference to the MEaSURES GLL is the automatic delineation of the grounding line from the double difference interferograms which is carried out through machine learning. The product consists of multitemporal GLL segments with large spatial spread and in some areas looking unrealistic. Moreover, this product – similar to the MEaSURES GLL - has no annotation in the attribute table of the exact time stamp of the Sentinel-1 acquisitions. Therefore, we do not consider this data set appropriate to be used for the validation of the AIS_cci GLL products.

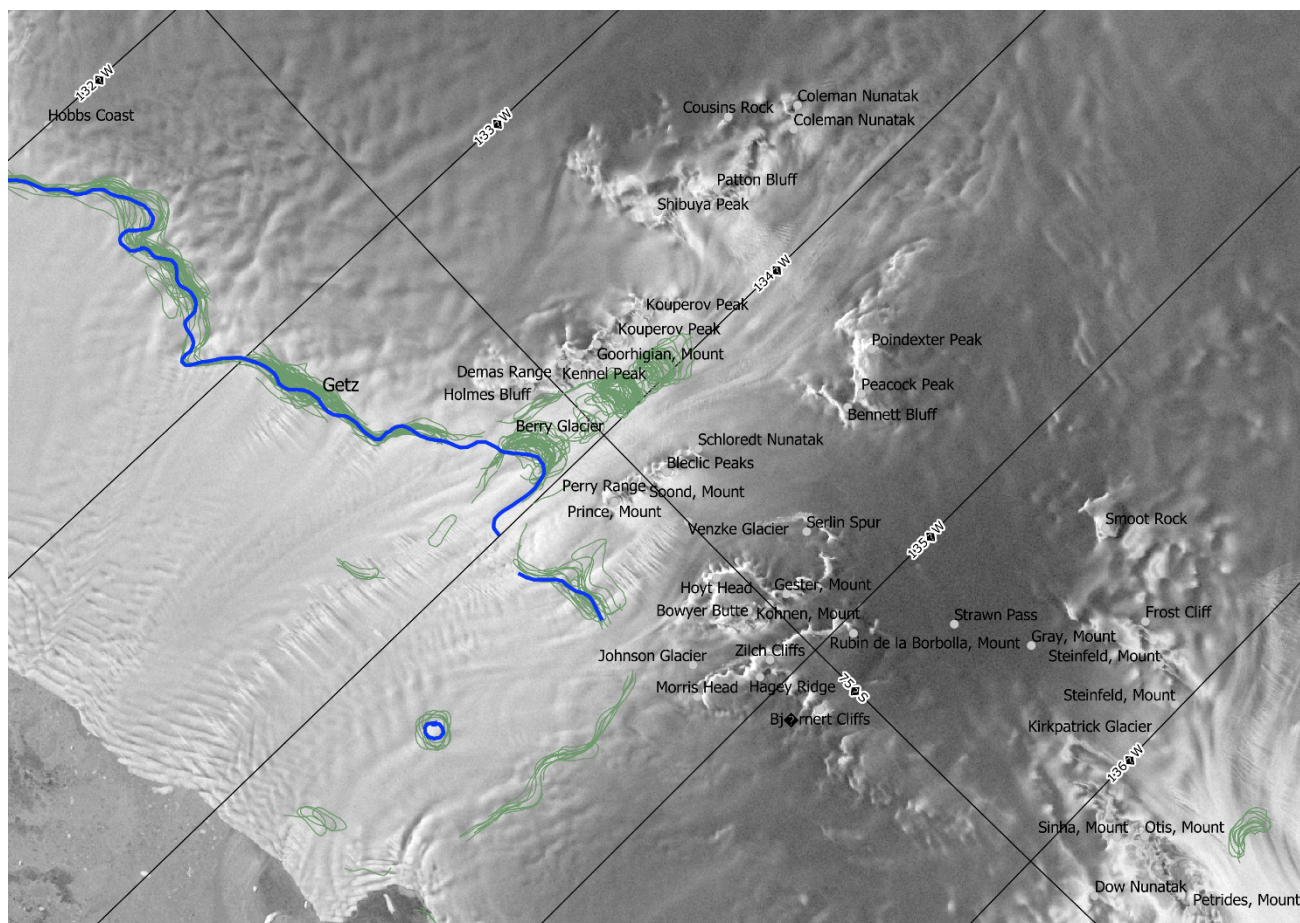


Figure 4-1: The AIS_cci GLL (blue line) and the time series of machine learning delineated GLLs (green lines) in the Getz area.

4.1.3 Assessment

Although the term “grounding line” is generally used to define the boundary of the grounded ice sheet and a floating ice shelf it can be applied to various datasets using different methodologies sensitive to different topographic or dynamic features. In order to avoid confusion when the different grounding line products are compared with the AIS_cci GLL the processes and features at the margin of the ice sheet are schematically outlined in Figure and will be discussed in the following.

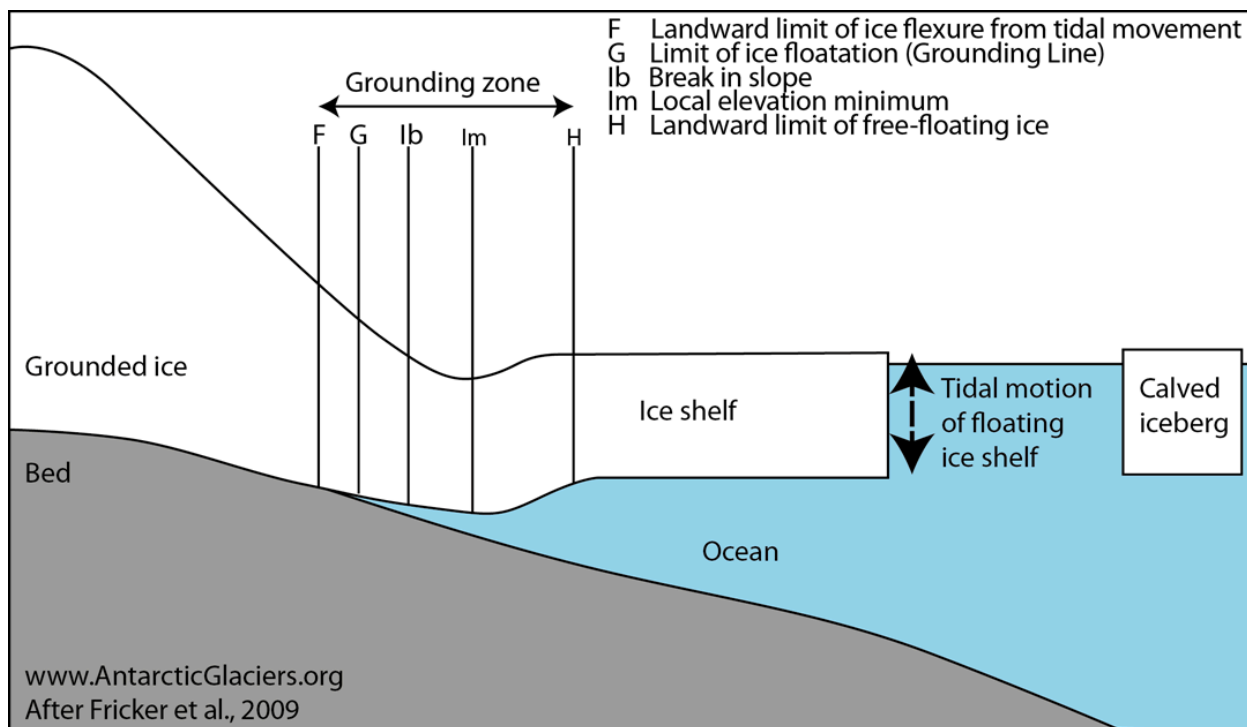


Figure 4-2: Processes and features at the grounding zone.

The flexure zone extends between the point F, the most seaward point not vertically displaced by tidal flexure, and H, the most landward location that experiences vertical motion equal to the magnitude of the ocean tide. G is the location where the ice loses contact to the bed (at low tide). I_b and I_m are inflections of the surface slope where the slope changes most rapidly (break in slope) and where the slope is zero, respectively. Different techniques determine different points within the flexure zone. H is not well known, but F and I_b have been extensively mapped.

The MOA and ASAlD grounded ice boundaries (GLLs products) are most consistent with point I_b , the break in slope. SAR sensors detect the band of flexure between F and H which appears as a typical pattern of dense fringes in the double difference interferograms. Although F is not identical with G, since F and G lie very close together (< 1 km) (Rignot et al., 2011b) the upper limit of flexure is treated as the GLL. This is the case for MEaSURES and AIS_cci (see RD4) products. Repeat laser altimetry can detect H and F from repeat-track analysis and I_b and I_m from single profiles (Bindenschadler et al., 2011).

The zone F-H is typically 2-11 km wide on Antarctic glaciers but can also reach extreme values of up to 25 km in areas that are lightly grounded or where tidal flexure is highly contorted by boundary conditions. I_b is typically a few km downstream of G.

4.1.4 Selection

The AIS_cci grounding lines are validated against the independent datasets described in Section 4.1.2. The comparison is carried out on four areas (Figure 4-3). Additionally, the Schirmacher site has been divided into one area covered by Sentinel-1 and one area where ERS-1/2 data was used.

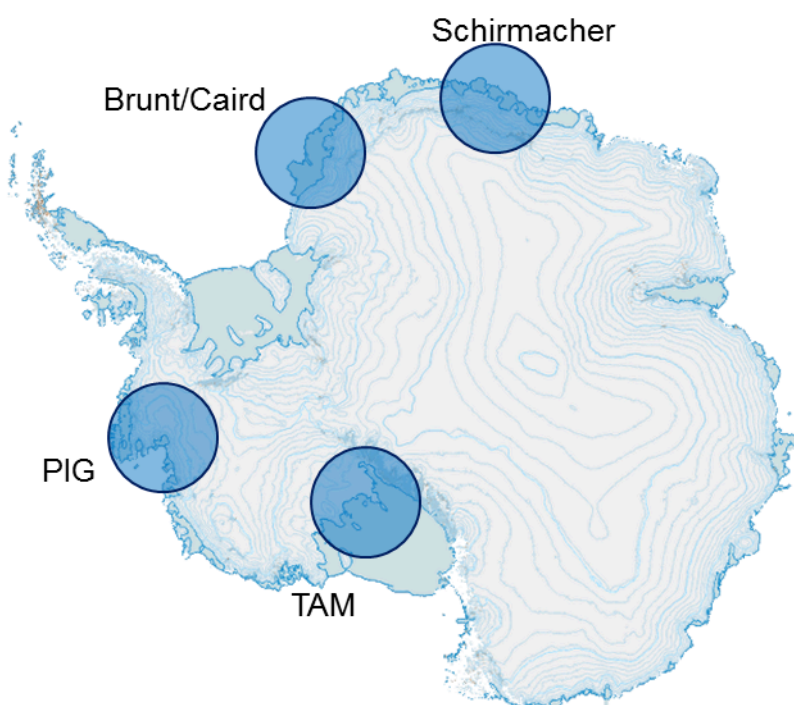


Figure 4-3: Validation test areas for the AIS_cci GLL products: Schirmacher, Brunt/Caird, PIG – Pine Island Glacier and TAM – Transantarctic Mountains.

4.2 Validation procedure

For the validation, the GLLs are compared with a spatial metric. A tide level dependent comparison is a goal for further comparisons later in the project but it is currently difficult to perform since no exact acquisition times are given in the other datasets. Using MEaSUREs date stamp and orbit number theoretically allows the determination of the actual acquisition time required for tide prediction. The change of the grounding line position with the ocean tide is currently an actively researched scientific topic, therefore it is still preferred to compare grounding line delineations from the same satellite acquisitions under the influence of the same ocean tide state.

We carry out our analysis in two parts. First the AIS_cci machine learning delineations are validated against manual delineations on the same double difference interferogram. The detailed intercomparison setup is described in (Ramanath et al., 2025).

Then, validation of the manual delineations is performed in four areas and compares AIS_cci GLLs with each of the GLLs described in the validation set (Section 4.1.2). If there is more than one GLL in a specific validation product all of them will be analyzed, since no temporal separation is currently performed.

The different GLL datasets are referenced as:

Reference	Description
AIS_cci	Our product derived from interferometric data
ASAIID	ASAIID GLL
MOA	MOA GLL
MEaSURES	MEaSURES GLL

All GLLs superimposed on the RSat-1 SAR backscattering mosaic are shown in Figure 4-4 to Figure 4-8. A first visual comparison suggests a good overall agreement between all GLL products within a range of 5 km to 10 km.

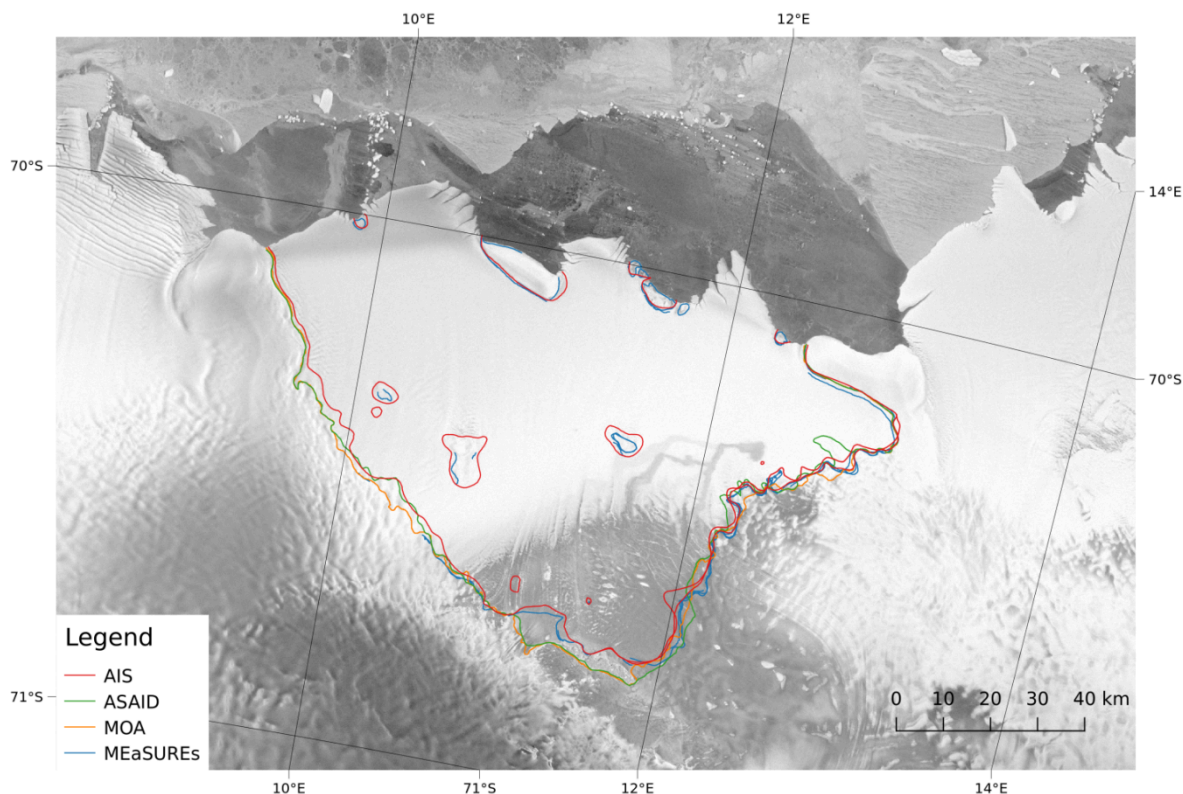


Figure 4-4: The Schirmacher ERS area (Nivlisen Ice Shelf) with all validation GLLs and the AIS GLL derived from ERS-1/2 data.

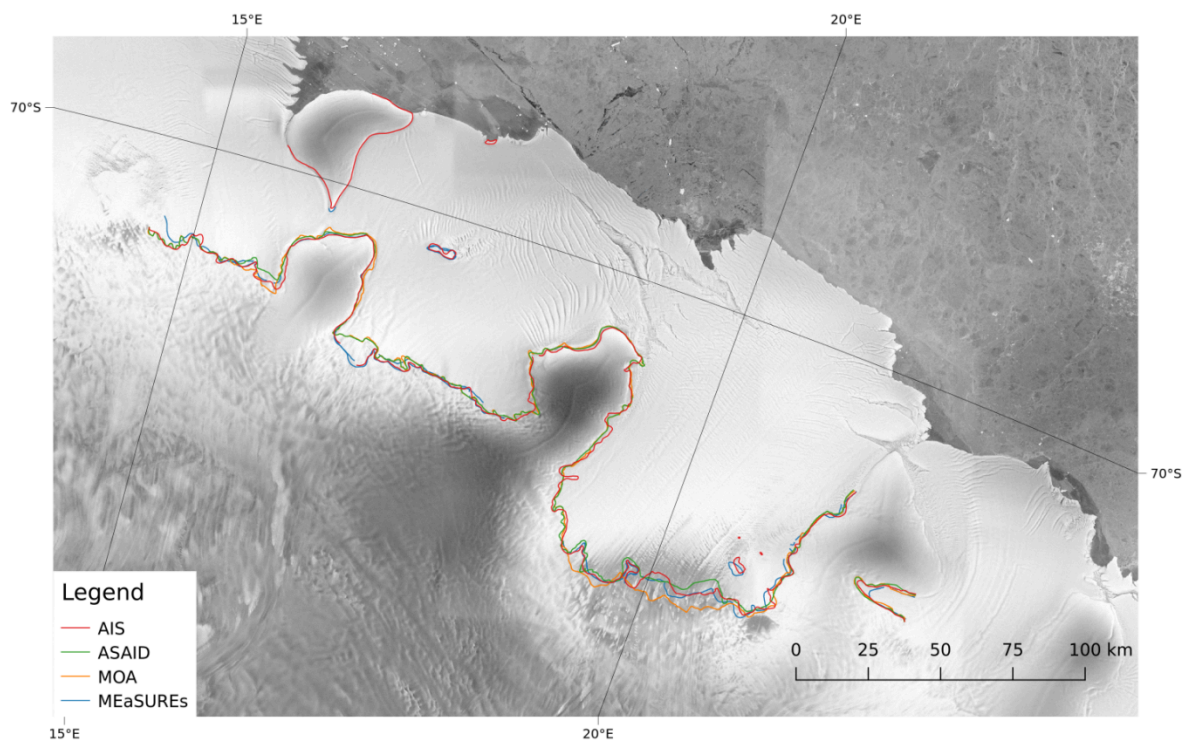


Figure 4-5: The Schirmacher S1 area (Lazarevisen Ice Shelf) with all validation GLLs and the AIS_cci GLL derived from Sentinel-1 data.

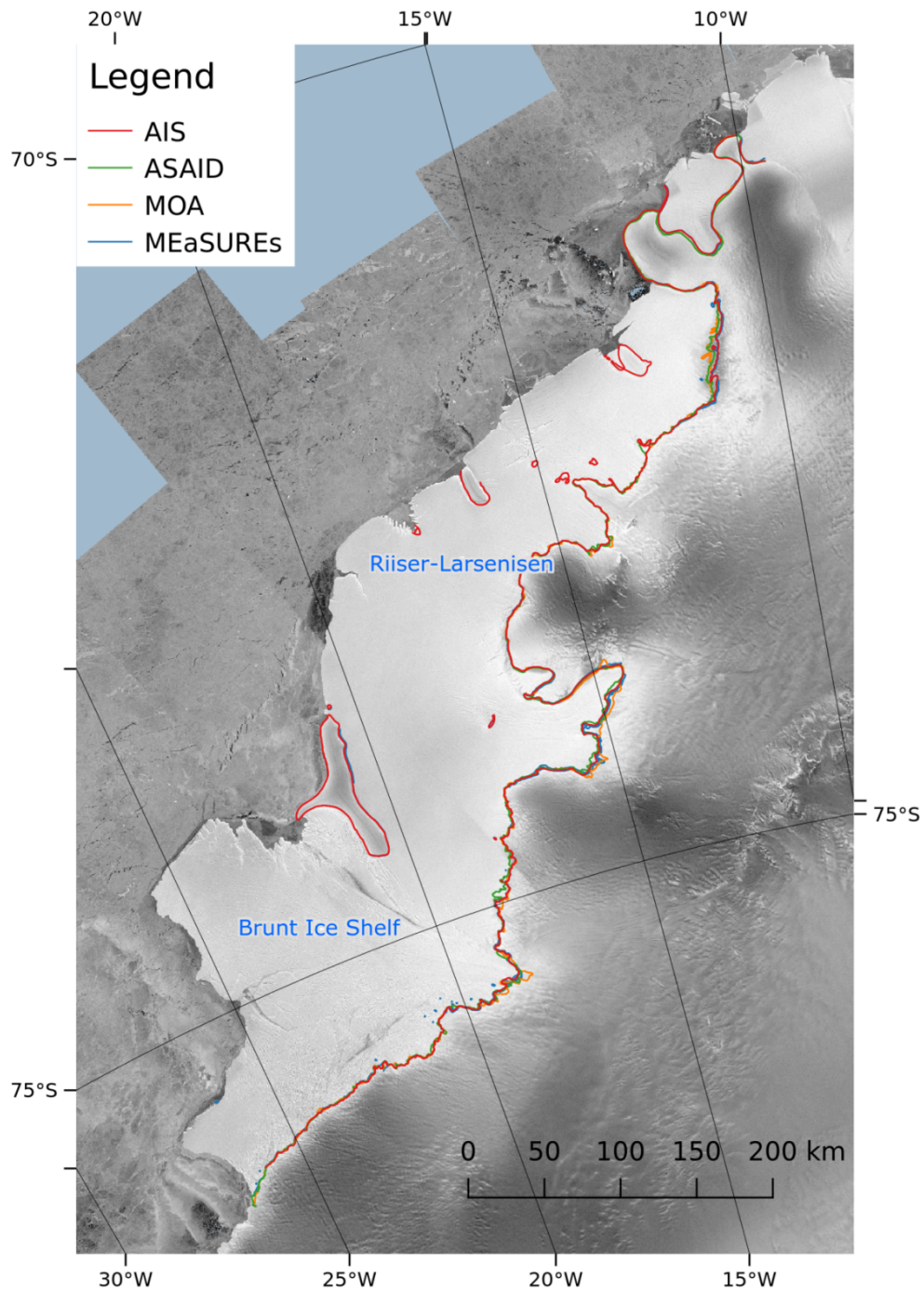
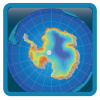


Figure 4-6: The Brunt Ice Shelf/Caird Coast area (incl. Riiser Larsenisen Ice Shelf) with all validation GLLs and the AIS_cci GLL derived from ERS-1/2 data.

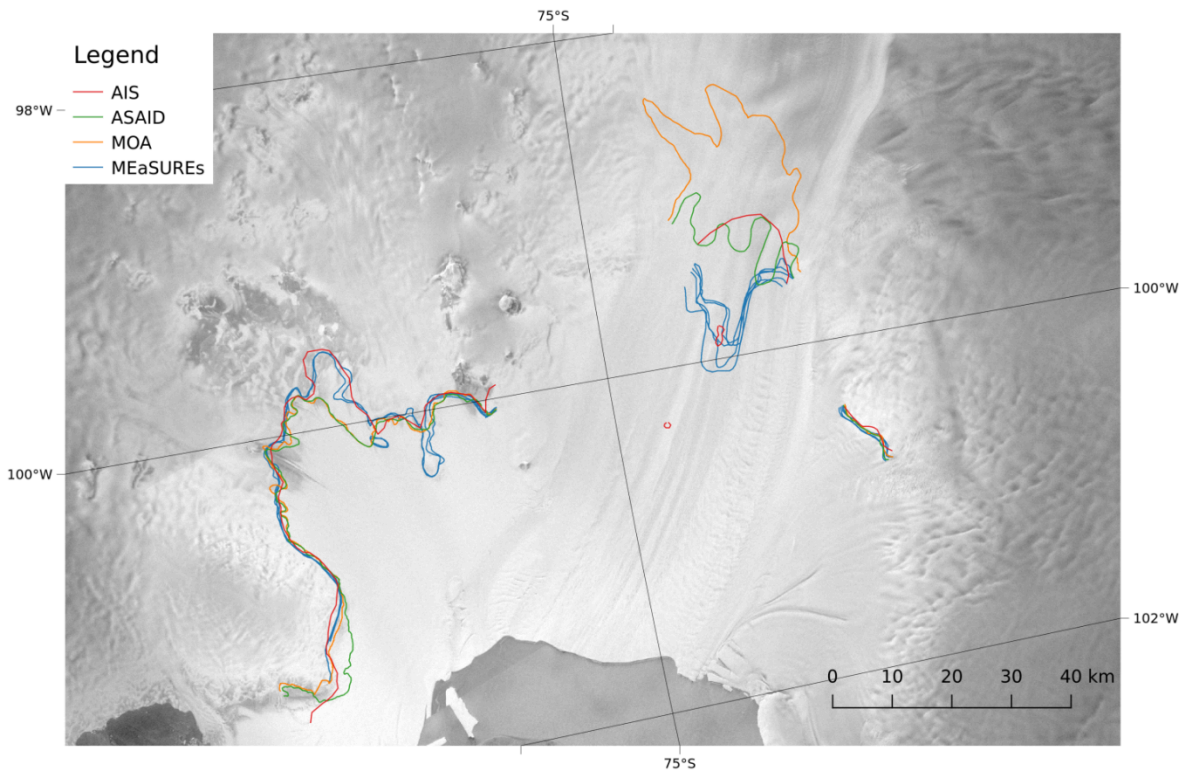
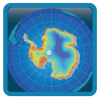


Figure 4-7: The PIG area with all validation GLLs and the AIS GLL derived from ERS-1/2 data.

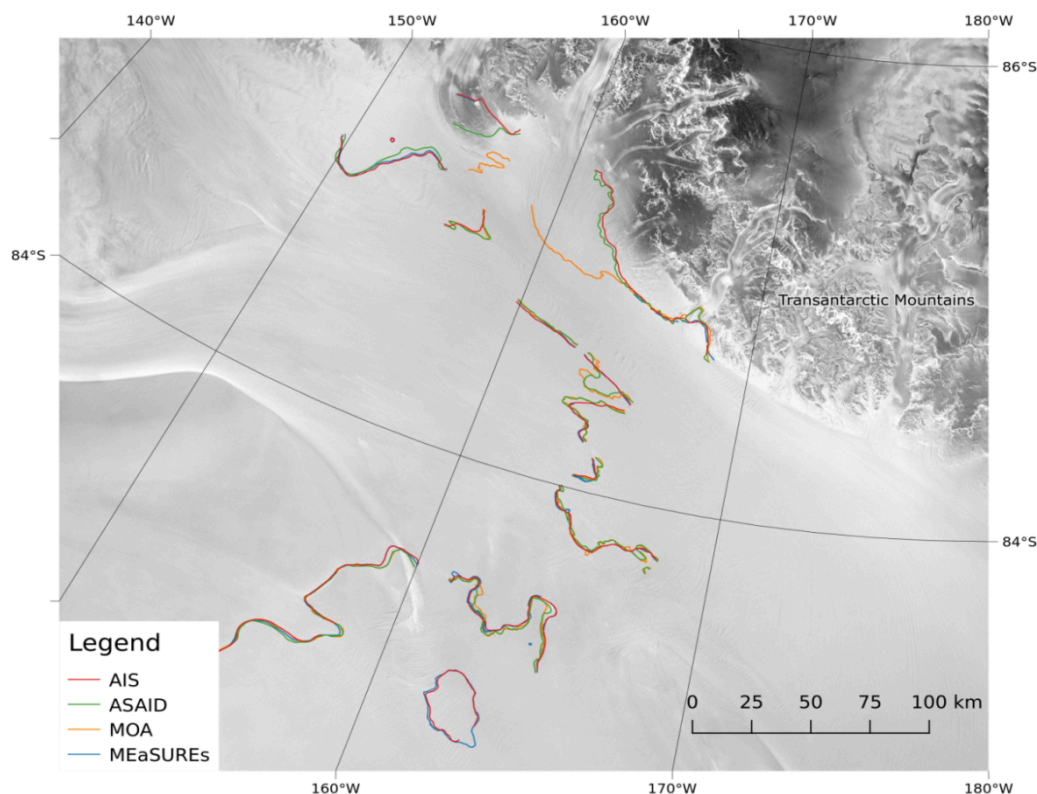
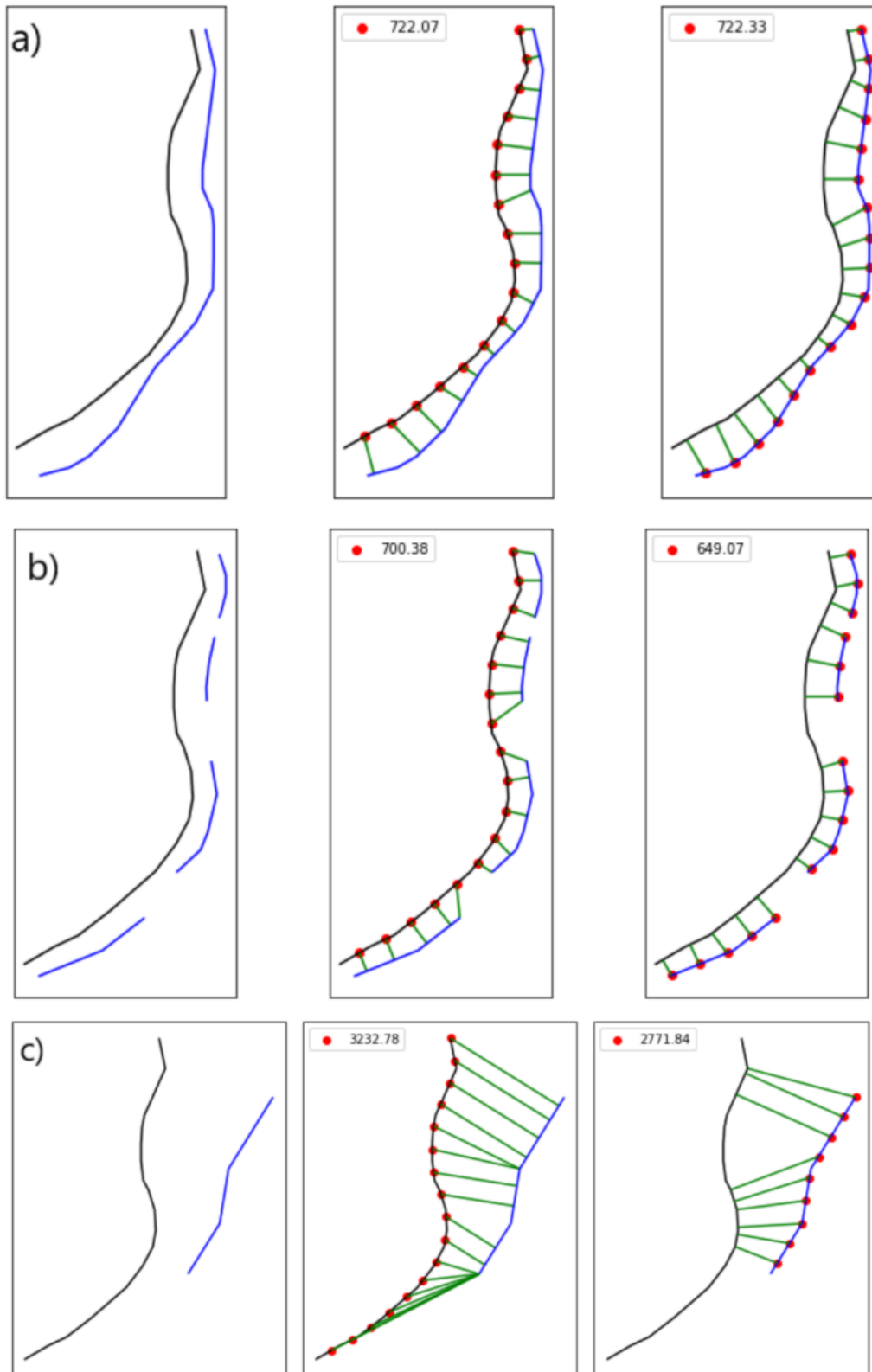
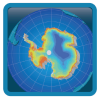


Figure 4-8: The TAM area (Southern Ross Ice Shelf and Transantarctic Mountains) with all validation GLLs and the AIS_cci GLL derived from TerraSAR-X data.

To quantify the differences among the various GLLs a polygon comparison procedure has been adapted to project's needs and has been implemented for the purpose of validation. All selected validation lines and our product are represented as two-dimensional polylines. Polylines are collections of points with a defined connection.

A problem which occurs if two polylines are compared is that there is no defined mapping between the points belonging to the reference line and those belonging to the target line, respectively. Moreover, the sampling of both polylines may differ significantly. This implies that a distance between points cannot automatically be calculated for each point without defining a line-to-line (or point-to-point) assignment. One solution which provides a mapping between two lines is the assumption that for each point on the target line, the closest point found on the reference line is the corresponding point. It is important to note, that even if the same mapping technique is used the result of the assignment may vary depending on which lines are selected as target and reference, respectively.

In the latest literature, the polygons and line segments (PoLiS) metric (Avbelj et al., 2014) has been increasingly adopted to compare lines and polygons because it performs a two-way comparison of the geometries. Figure 4-9 highlights the directional effect of line-to-line distance. The PoLiS metric essentially computes the average of these distances.



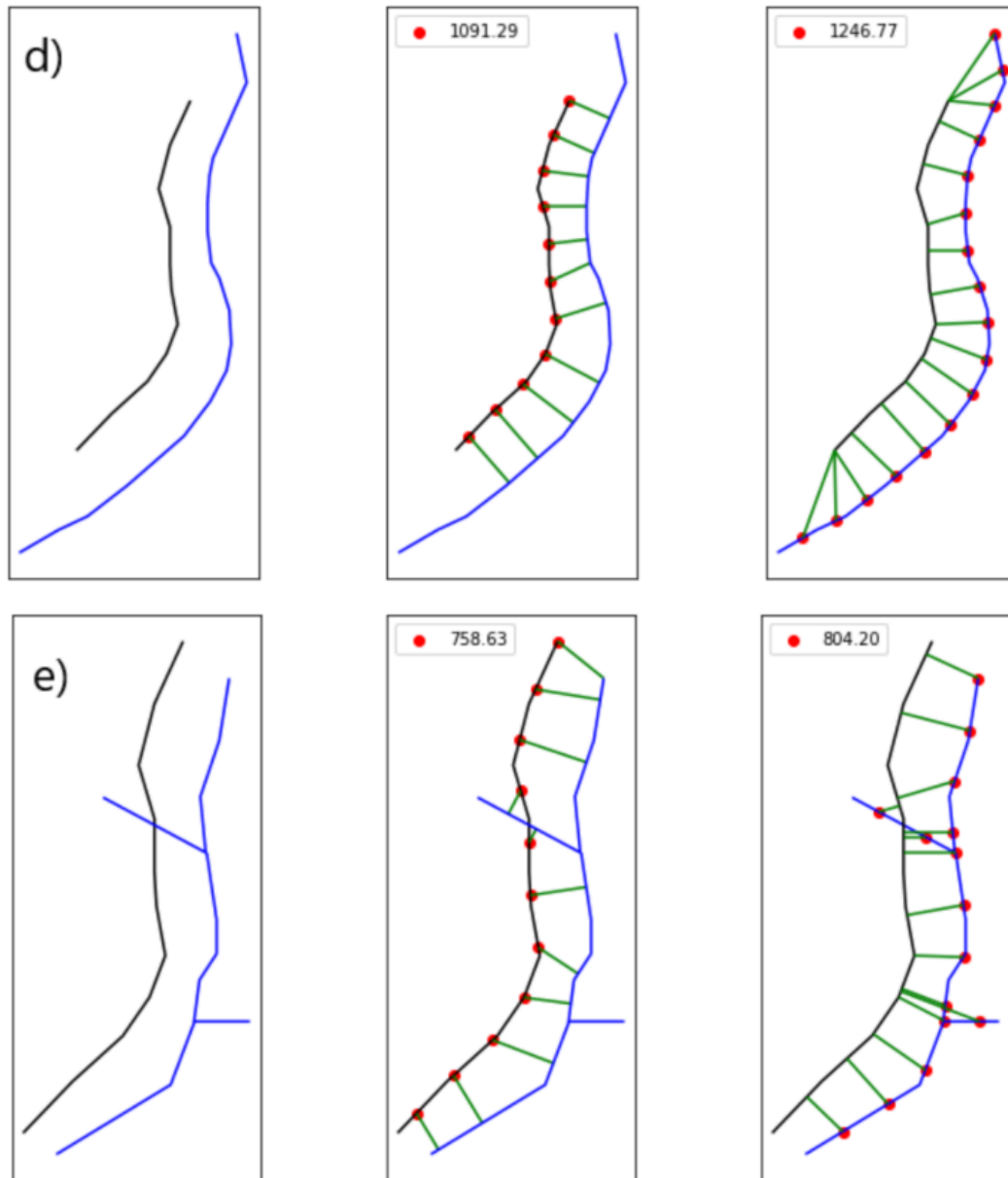
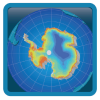


Figure 4-9: Computation of line-to-line distances for several reference (black) and target (blue) configurations. Column 2 visualises the reference to target distance and column 3 shows the target to reference distance. The distances are measured from red points on one line to its closest point on the other line. Respective distances (metres) are shown in the legend. Configuration a) ideal case where target follows the reference closely b) target is fragmented but still within the length of reference c) target is far away and shorter than the reference, d) target length exceeds reference distance and e) spurious branches on the target.

In a similar metric to PoLiS, we visualise minimal distances around a line to creating a region around it. This object is called a buffer. One example of using a buffer around a polyline is shown in Figure 4-10. The buffers around the AIS_cci GLL, defined as reference line, are increased until the target line (ASAID GLL) is completely

contained within the buffer (e.g. at 5000 m distance). The overlap with the target line can be calculated for selected buffer distances. These buffers can then be used to calculate the overlap (expressed in percentage) with other lines at a specific distance.

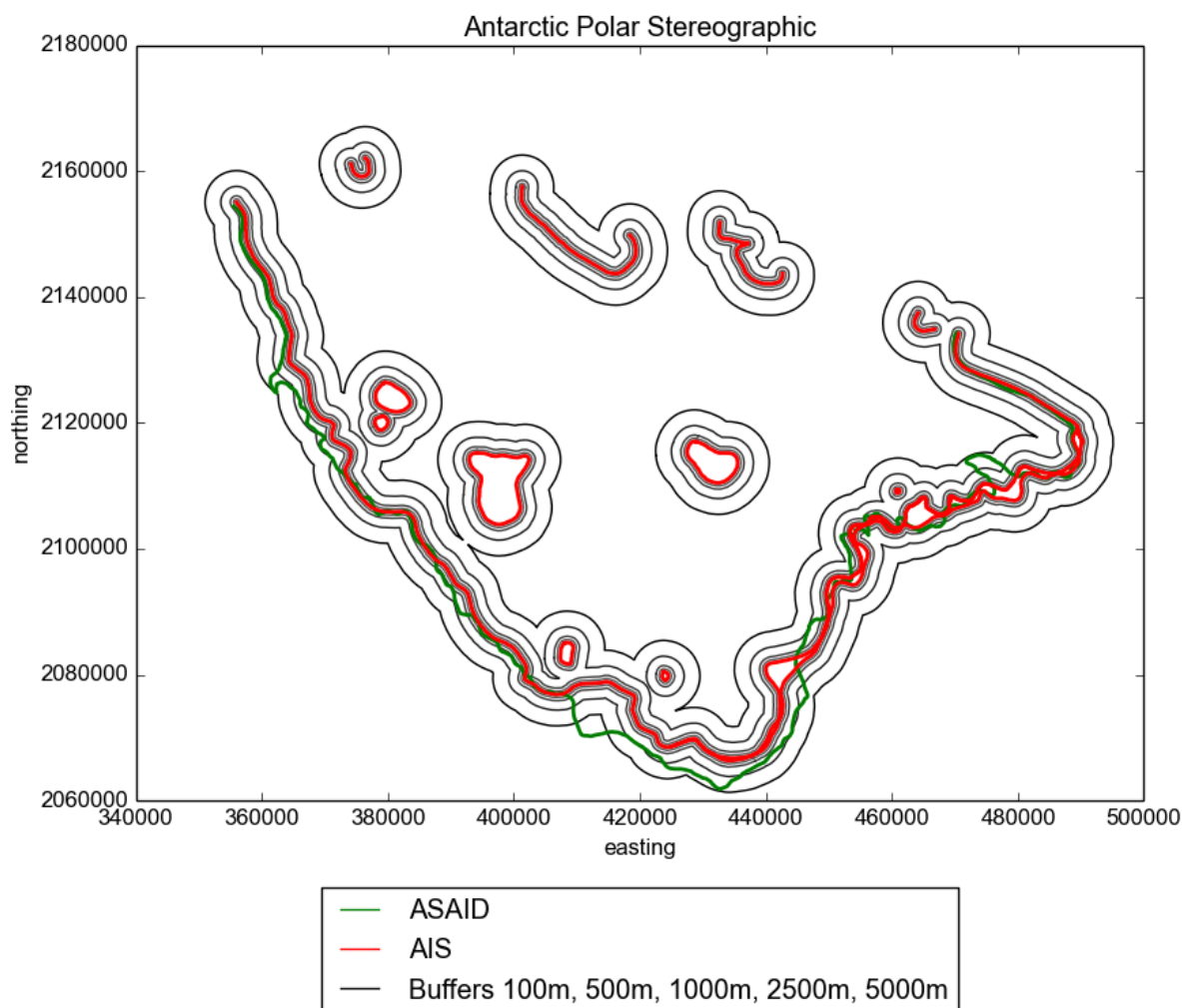


Figure 4-10: Buffers (black lines) corresponding to different distances around the AIS_cii GLL (reference line, in red). The target line is the ASAID GLL (in green). At the largest distance of 5000m the green line is almost completely contained within the buffer.

Using buffers is very intuitive but at the same time also problematic e.g. if polyline segments have very different sampling intervals or if the buffers shall be determined in very small steps in order to get more precise results. Because of this we decided for a more generic approach – a proximity image – which is simply another implementation. The reference polyline is represented in a binary image and the shortest distance for each pixel in the image to the reference line is determined and stored as value at this point. The spatial sampling of that image is 5 m x 5 m which therefore is the smallest detectable difference. Such a proximity image is shown in Figure 4-11.

All datasets which shall be validated are now equally resampled and superimposed onto this image. Depending on the shape of the polyline these datasets will cross different “distance values” of the proximity image. All the values which will be encountered if one traverses along the GLL of the validation dataset result in a histogram (left side plots on Figure 4-14 to Figure 4-18). The more values obtain shorter distances, the better the final fit will be. Similar to PoLiS, besides the histogram characteristics, the mean values of the distances also quantify the equality between two polylines and are given in Table 4-3.

In order to show how well the target lines are approximated by the AIS_cci we also determine how much of the other curve is covered by the reference curve within a predefined buffer size. This step is repeated for different continuously growing buffer sizes. A plot of the overlap (in percentage) against the buffer size is generated for each of the target lines in each of the validation sites. This is called a Cumulative Ratio Curve (CRC) and is similar to a Cumulative Density Function of a distribution (Heo 2009), (Jeong 2013). The CRCs are

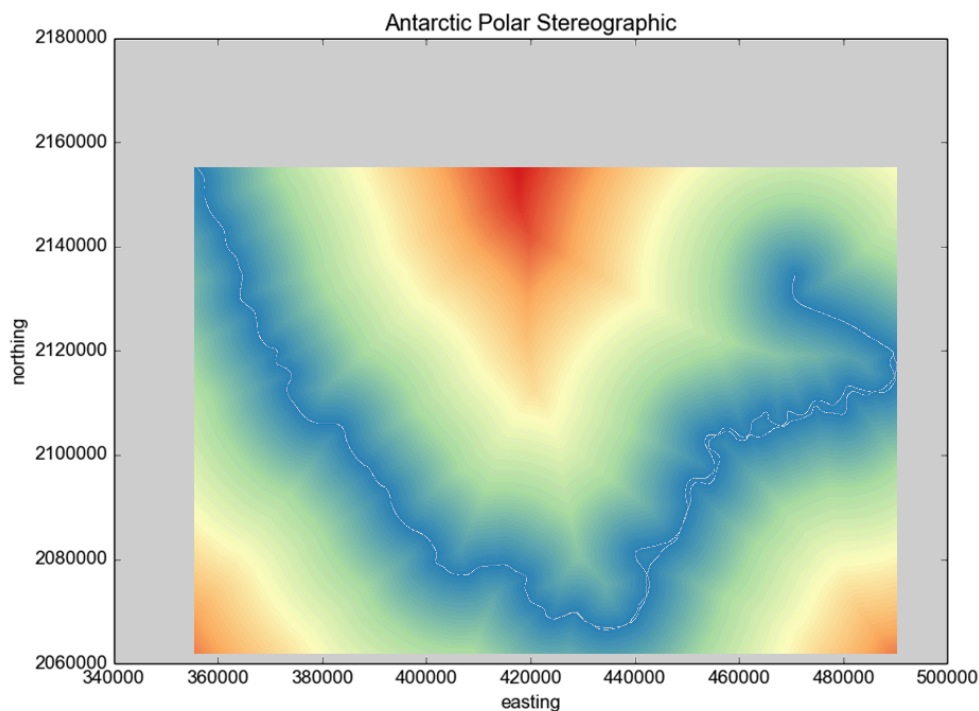


Figure 4-11: Proximity image for AIS_cci GLL at Schirmacher derived from ERS. The color scale from blue-green-yellow-red depicts increasing distances to the polyline. The white line is the reference AIS_cci GLL.

shown on the right-side plots of Figure 4-14 to Figure 4-18.

4.3 Validation outcome

4.3.1 Comparison of machine learning vs. manual delineations

The validation procedures for the automatically delineated lines are documented in (Ramanath et al., 2025). In the peer-reviewed journal publication, multiple network layouts and their variants have been discussed in detail. In this report, we present validation results only for the two best-performing network configurations (see Table 4.1). The network which is finally selected for the AIS_cci machine-learning line generation is highlighted in bold.

Table 4-1: Network variants used for intercomparison against manually delineated AIS_cci grounding lines. The selected network for final automatic grounding line delineation is highlighted in bold.

Network variant	Description
Rect + Non-Intf	This network variant was trained on the double difference phase information represented in rectangular form of real and imaginary part (Rect). Additionally, the network evaluated a stack of non interferometric features (Non-Intf) containing surface elevation, ice velocity and differential tide. This is the selected network for AIS_cci production.
Rect	This network variant was trained on the double difference phase information represented in rectangular form of real and imaginary part (Rect), only. No additional non interferometric features are evaluated.

Figure 4-12 illustrates a GLL delineation example produced by the two network variants. For each variant, five independently trained models were combined into an ensemble to estimate prediction uncertainty.

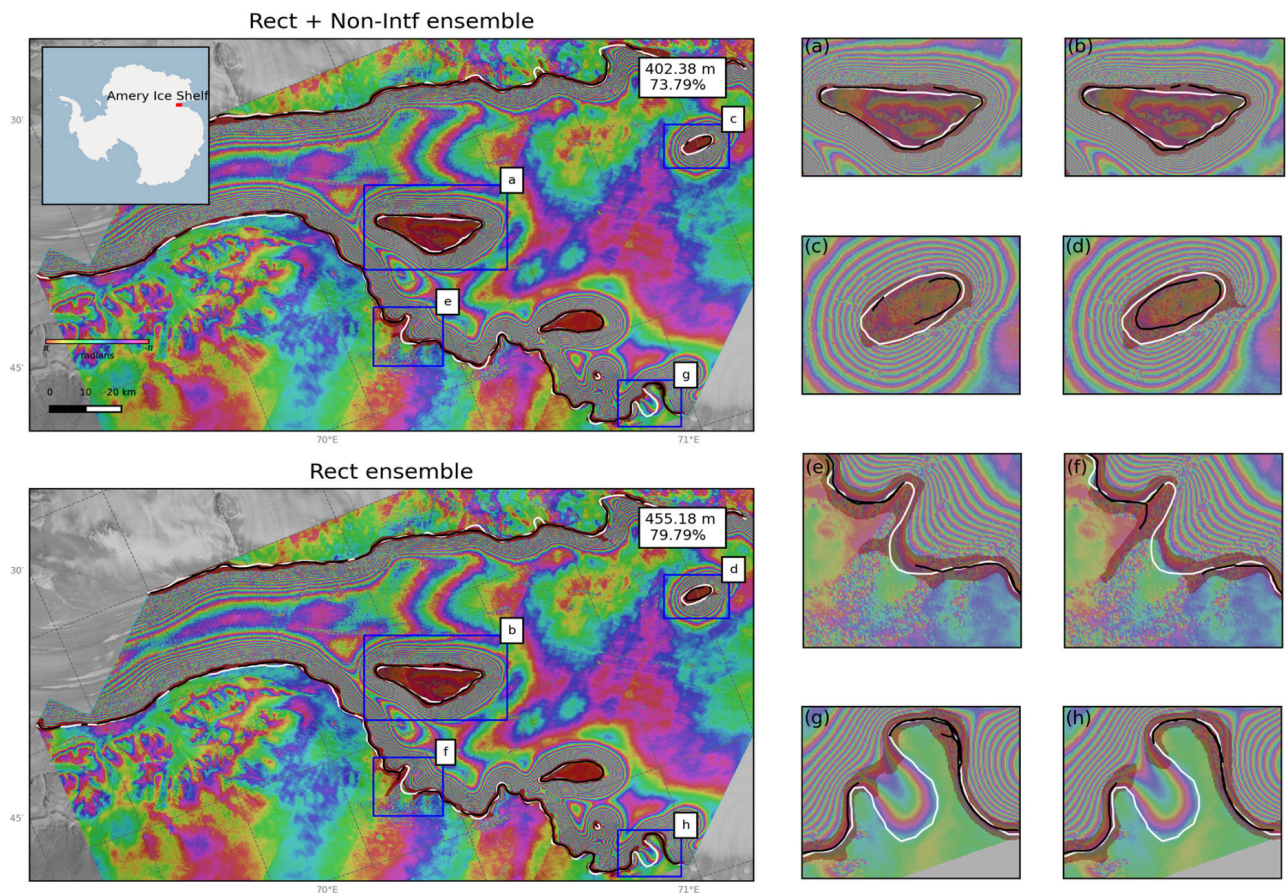


Figure 4-12: Manual GLs (white) and machine learning delineations of the ensemble networks (black) of the Amery Ice Shelf test sample. The predictive uncertainty is depicted as the shaded region enveloping the lines (red). The inset shows examples of regions where the width of the uncertainty buffer extends into features such as the (a, b) Clemence Massif and (c, d) Budd Ice Rumples. The models are also uncertain over (e, f) partially decorrelated fringes and (g, h) loose fringes.

The ensembles were validated against manually drawn grounding-line annotations from the AIS_cci datasets, and their statistical performance metrics were computed accordingly. For details on the validation dataset, please refer to (Ramanath et al., 2025).

Table 4-2: Performance of ensemble networks. The metrics are calculated for the ensemble average GLs. The predictive error is computed as the average of one-way distances from the average GLs to the nearest uncertainty buffer contour. Abbreviations for feature subsets are as follows: Rect – real and imaginary components (rectangular representation); Non-Intf – non-interferometric features.

Network variant	Median distance [m]	Mean distance [m]	Predictive error [m]	MAD [m]	Mean coverage [%]
Rect + Non-Intf	222.2	340.5	373.9	109.4	69.0
Rect	265.0	421.09	401.8	140.6	65.2

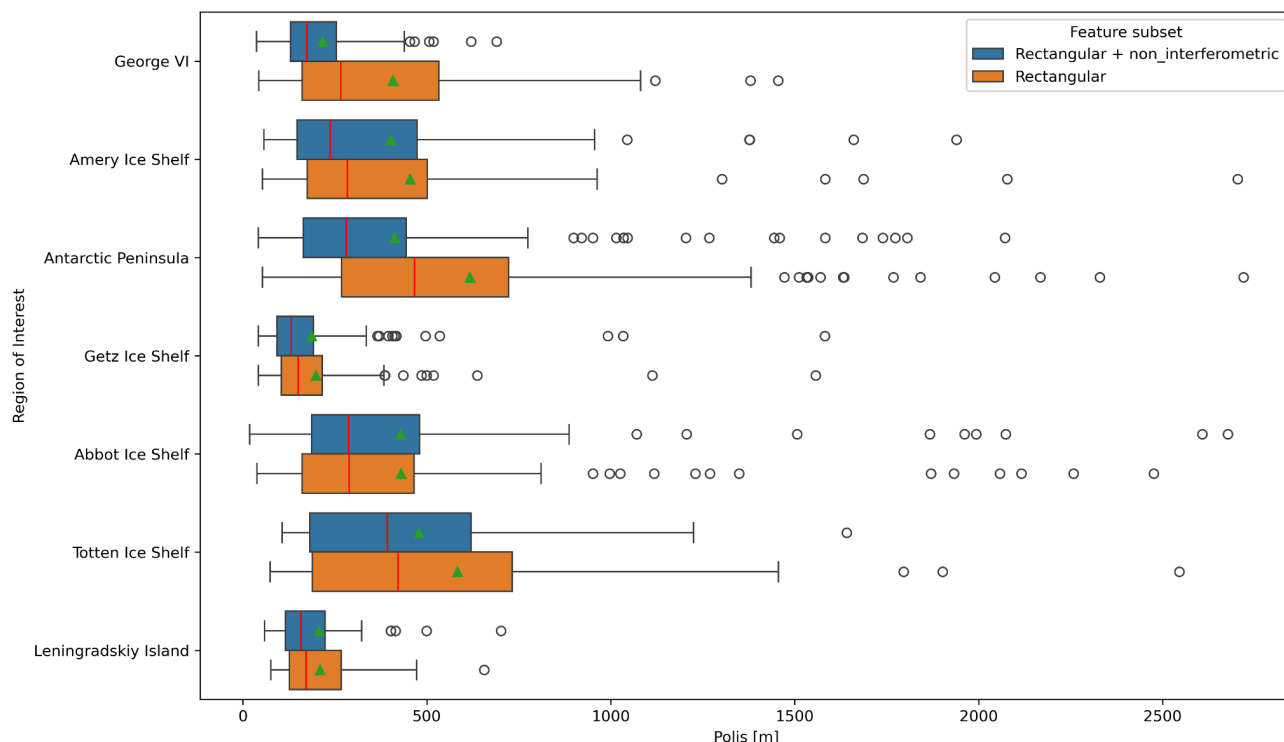


Figure 4-13: Region-wise performance of the two ensembles. The green triangle and the red line indicate the mean and median distances, respectively. The circles outside the whiskers are outliers, which lie outside 1.5 times the interquartile range

4.3.2 Intercomparison of manual lines against other grounding line products

We performed the validation procedure on each of the four areas by comparing the AIS_cci GLLs with the independent validation dataset. Each comparison yields an average minimal distance between the lines which represents the mean value of “difference” between the participating lines (Table 4-3). For each comparison the histograms and CRC curves described in Section 4.2 were generated (Figure 4-14 to Figure 4-18). In addition, we compared a segment of the grounding line which was generated from the same SAR dataset within two different projects, MEaSURES and AIS_cci (Section 4.3.7).

Table 4-3: Mean of the distances between the AIS_cci GLL and the respective validation candidates.

	d_{ASaID} [m]	d_{MOA} [m]	d_{MEaSURES} [m]
Schirmacher ERS	1372	1481	599
Schirmacher S1	782	1056	688
Brunt/Caird	666	953	446
PIG	1871	5625	3649
TAM	2039	4016	573
Average (all areas)	1328	2626	1191
Average (excl. PIG)	1215	1877	576

In the PIG area the mean distances AIS_cci vs. MEaSURES have to be interpreted with care because the MEaSURES dataset contains a time series of GLLs which vary significantly in locations (up to 12 km). In this case the overlap ratio is < 1 even for big buffer sizes and reaches 1 at distances much larger than the 5000 m.

4.3.3 Schirmacher area

Schirmacher ERS

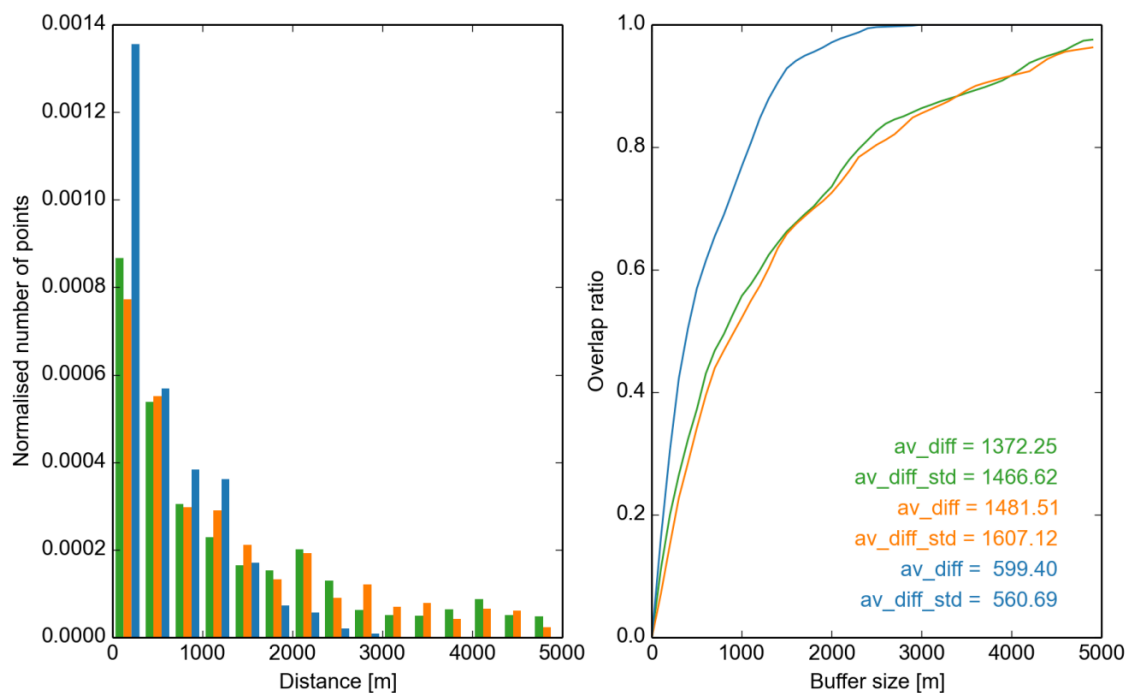


Figure 4-14: Comparison of the AIS_cci GLL line in the Schirmacher area derived from ERS data with the validation GLL: AIS_cci vs. ASAID (green), MOA (orange) and MEaSURES (blue). Left: histogram of the distances between the GLL lines. The number of points is normalised with respect to the area below the curve. Right: the Cumulative Ratio Curve.

Schirmacher Sentinel-1

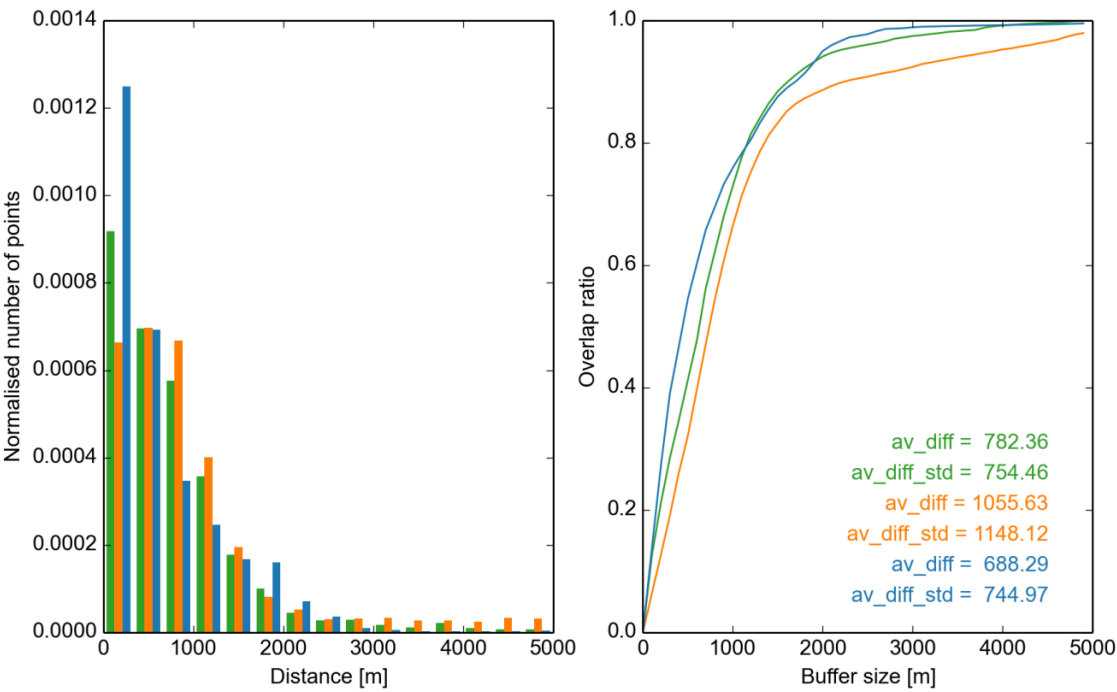


Figure 4-15: Same as Figure 4-11 but in the Schirmacher area. The AIS_cci GLL was derived from Sentinel-1 data.

4.3.4 Brunt/Caird

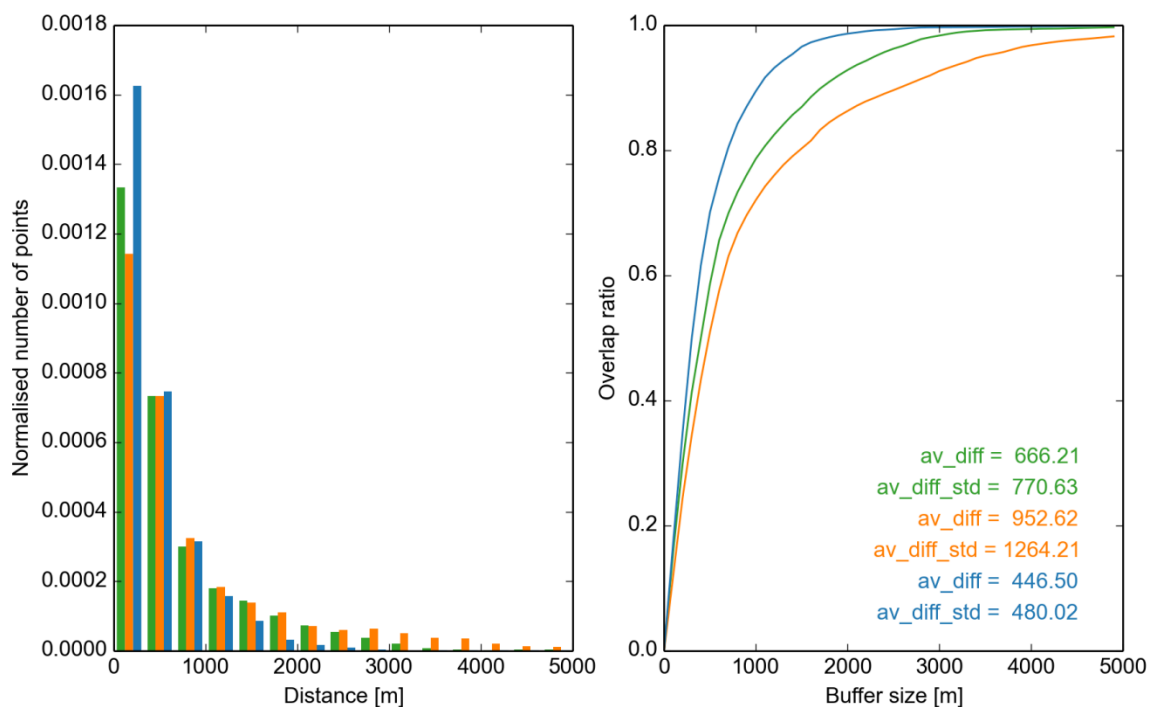


Figure 4-16: Same as Figure 4-11 but in the Brunt/Caird area. The AIS_cci GLL was determined from ERS-1/2 data.

4.3.5 PIG

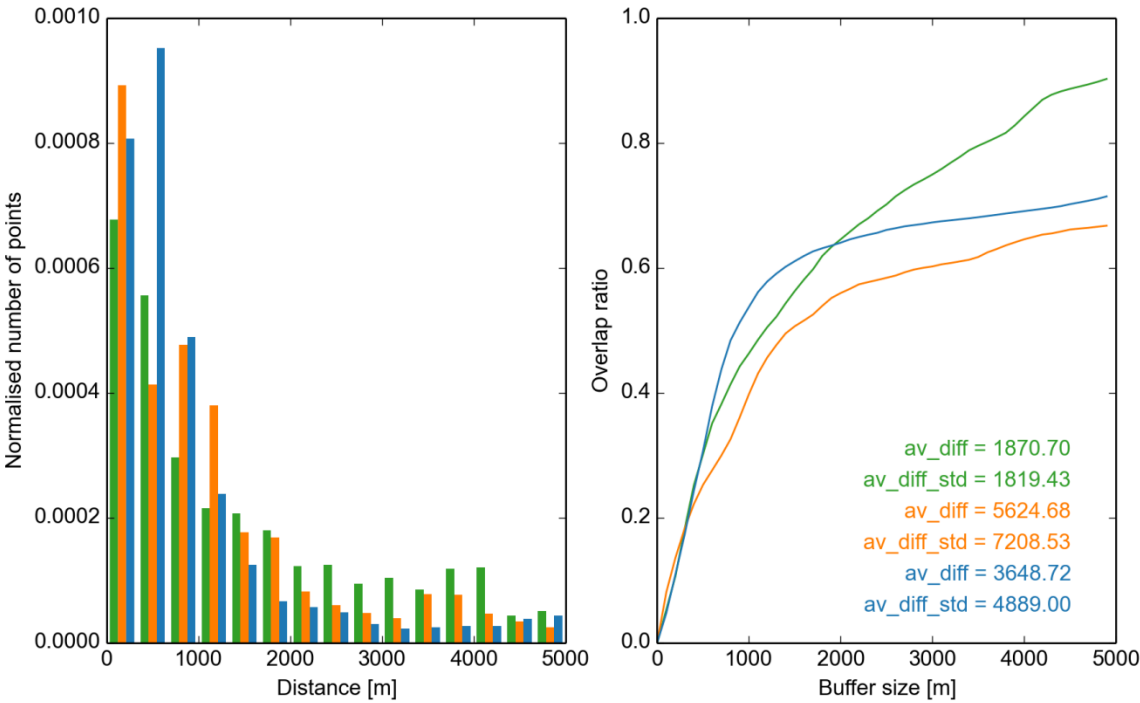


Figure 4-17: Same as Figure 4-11 but in the PIG area.

4.3.6 TAM

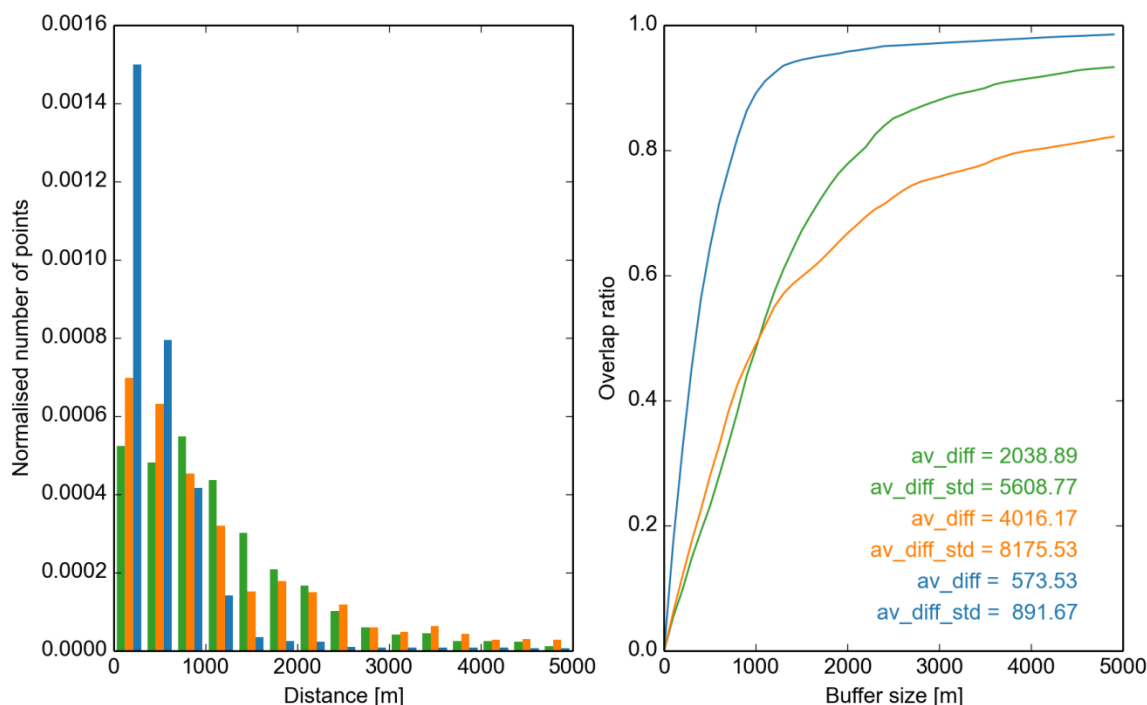


Figure 4-18: Same as Figure 4-11 but in the TAM area. The AIS_cci GLL was obtained from TerraSAR-X data.

4.3.7 Identical SAR datasets: MEaSURES vs. AIS_cci

For a validation that takes temporal variation of the GLL into account, we compare two AIS_cci GLLs against grounding lines generated within the MEaSURES project (Rignot et al., 2011b), (Scheuchl et al., 2016). In contrast to the comparisons shown above, this validation only concerns grounding line segments that have been produced from identical SAR acquisitions. In particular, we carry out two comparisons:

1. both AIS_cci and MEaSURES GLLs were created from Sentinel-1A satellite data acquired on the dates 2014-11-23, 2014-12-05 and 2014-12-17 (Figure 4-19a)
2. both AIS_cci and MEaSURES GLLs were created from ERS-1 satellite data acquired on the dates 1994-03-04, 1994-03-07 and 1994-03-11 during the 2nd Ice Phase (Figure 4-19b)

By using the identical SAR acquisitions, temporal variations between AIS_cci GLLs and MEaSURES GLLs due to tide level variations or grounding line retreat are excluded. The differences of the GLLs reflect the spatial accuracy of the grounding line delineation using the same methodology. Therefore, we expect smaller mean differences between these GLLs than in the comparison of the validation GLL products presented in section 4.3.2. From the visual inspection in Figure 4-19 it is obvious that both AIS_cci and MEaSURES GLLs overlap well on Dotson/ Crosson Ice Shelves and Jutulstraumen Glacier. Just in some areas on Dotson/ Crosson Ice Shelves neither AIS_cci GLL nor MEASURE GLL could be derived.

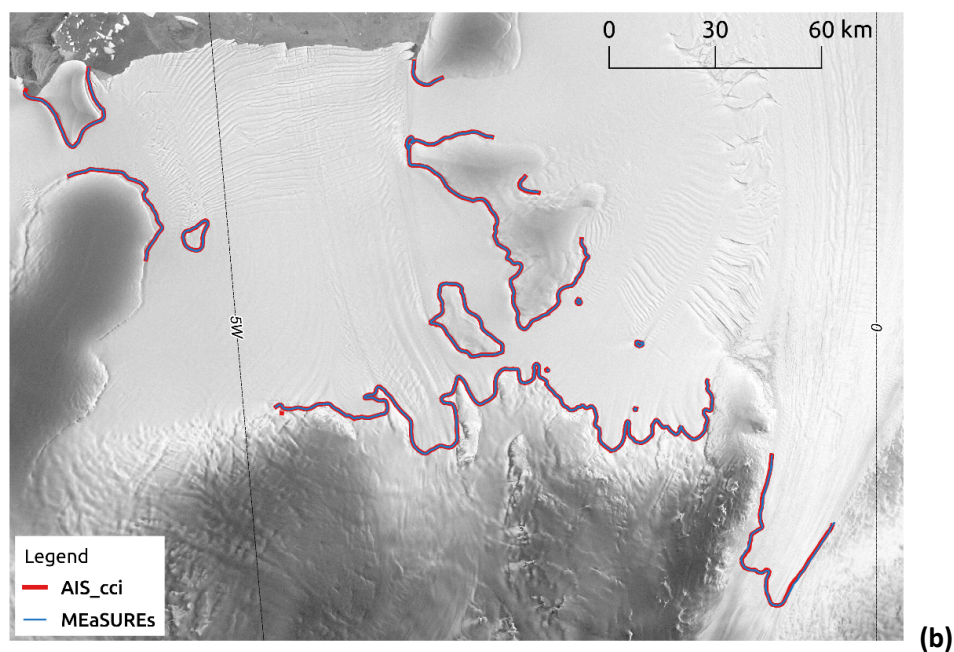
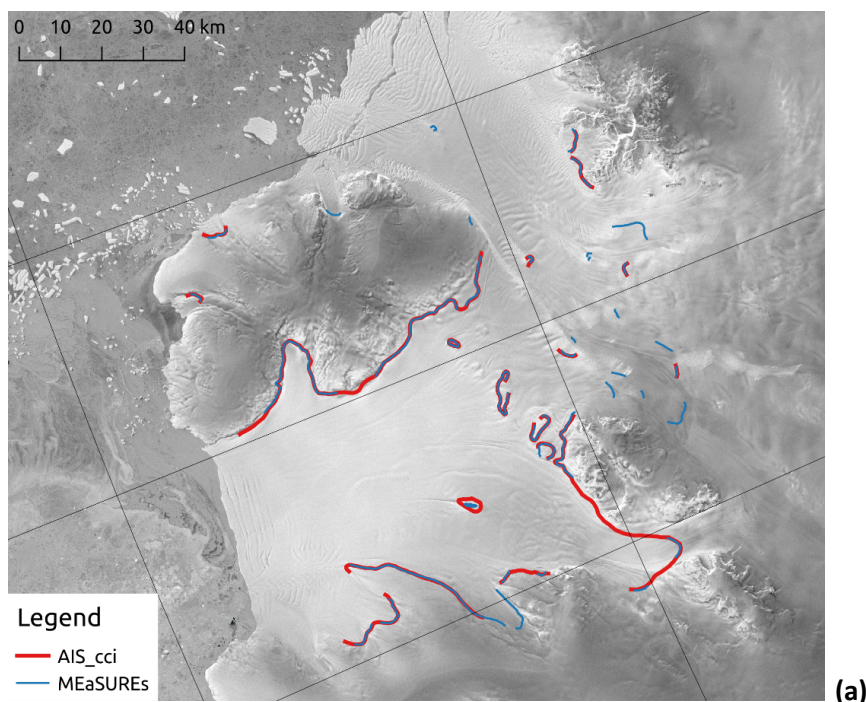


Figure 4-19: AIS_cci (red) and MEaSUREs (blue) GLL segments in (a) the Dotson/Crosson Ice Shelves area generated from the Sentinel 1A data triplet acquired on 2014-11-23/ 2014-12-05/ 2014-12-17 and (b) Jutulstraumen Glacier area generated from the ERS-1 triplet acquired on 1994-03-04/ 1994-03-07/ 1994-03-11.

We use the same methodology that was applied in the previous comparisons as a metric to report spatial differences of the GLLs. This time however, the comparison is done bidirectional, meaning that distances from each point defining the AIS_cci GLLs to the MEaSUREs GLLs are calculated and vice versa. The full comparison results are shown in Figure 4-20 to Figure 4-22. In Figure 4-20 all GLL segments, which are generated from identical Sentinel-1A triplet, are compared to each other even if they don't have a matching counterpart in the other dataset, while in Figure 4-21 and Figure 4-22 only GLL segments derived from Sentinel-1A and ERS-1 showing in both datasets are compared.

The two GLL products are following each other very well. Within a 500m buffer distance around the AIS_cci GLL 79% of the MEaSUREs GLL can be explained (red line in Figure 4-20 right). The fact that this ratio doesn't increase significantly with a growing buffer size means that about 20% of the MEaSUREs GLL has no matching counterpart in the AIS_cci dataset.

Similar is observed for the MEaSUREs GLL that has about 76% overlap with the AIS_cci dataset within the first 500m (blue line in Figure 4-20 right). The overlap increase at higher buffer distances is due to the fact that missing parts of the MEaSUREs dataset are often a continuation of the lines detected in AIS_cci GLL, whereas the parts that are missing from the AIS_cci dataset mostly stem from individual MEaSUREs GLL segments that are often far from other GLLs (see Figure 4-19a).

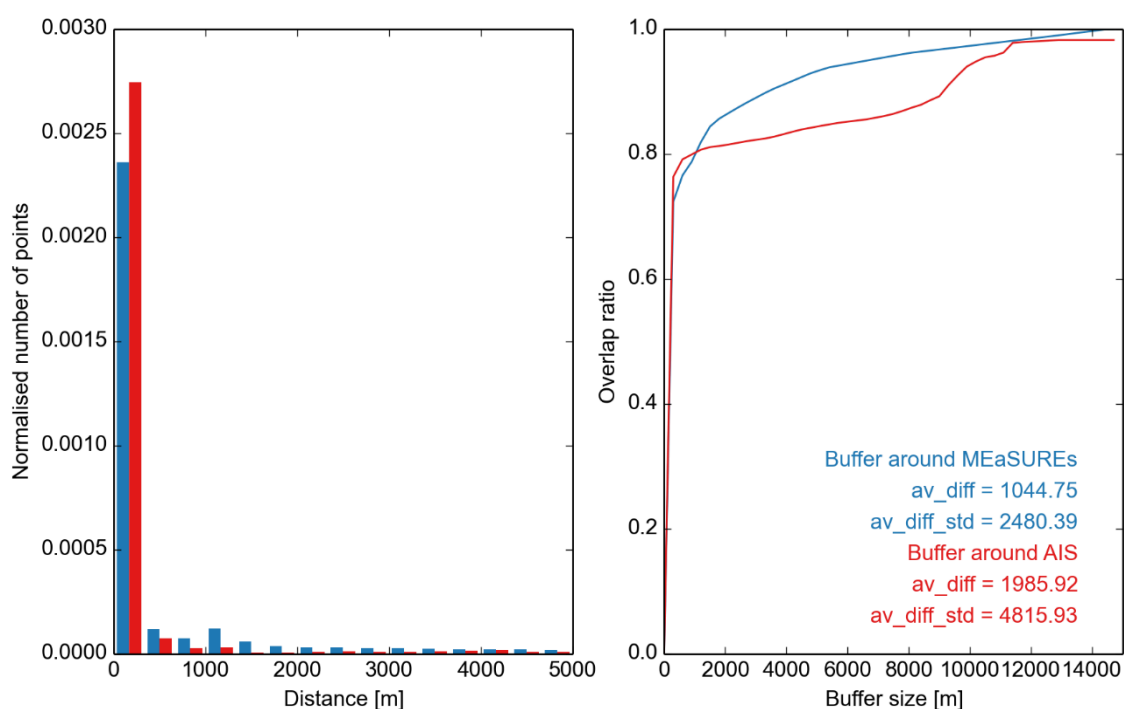


Figure 4-20: The bidirectional comparison results for GLL from identical Sentinel-1A acquisitions. All line segments are compared to each other. Left: histogram of the distances between the GLL lines. Right: Red line results when the distance from each point of MEaSUREs GLL to the closest point of AIS_cci GLL is calculated. Blue line results when the distance from each point of AIS_cci GLL to the MEaSUREs GLL is calculated.

To better assess the similarity of both GLLs, we only include GLL segments that have a mean distance of less than 5000m to its closest counterpart and therefore disregard line segments that don't have a matching representation in the other dataset. In Figure 4-21 we show the results and report mean distances of 129 and 173m for the two directions of comparison, respectively. As expected, there is now an almost complete overlap of the GLLs within small buffer distances. The remaining non-overlap is caused by line segments which have a small mean distance and are therefore included in the comparison, but that contain a number of points that have no matching counterpart. These are mostly line continuations where one candidate ends earlier than the other.

In Figure 4-22 the comparison is done between the GLLs which are derived from the ERS-1 triplet on Jutulstraumen Glacier. The bidirectional comparison shows that the mean distance is between 55 and 59m. Both GLLs are completely overlapped within 500m buffer distances.

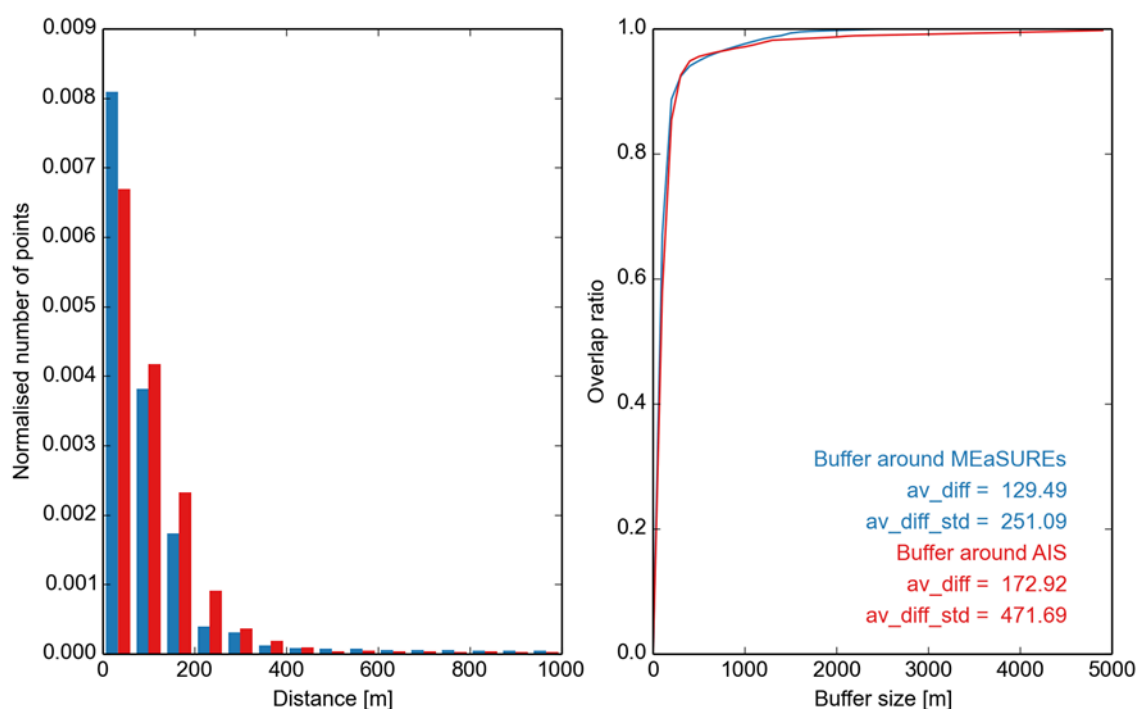


Figure 4-21: Same as Figure 4-20 but only GLL segments generated from Sentinel-1A data having counterparts in the two datasets are considered.

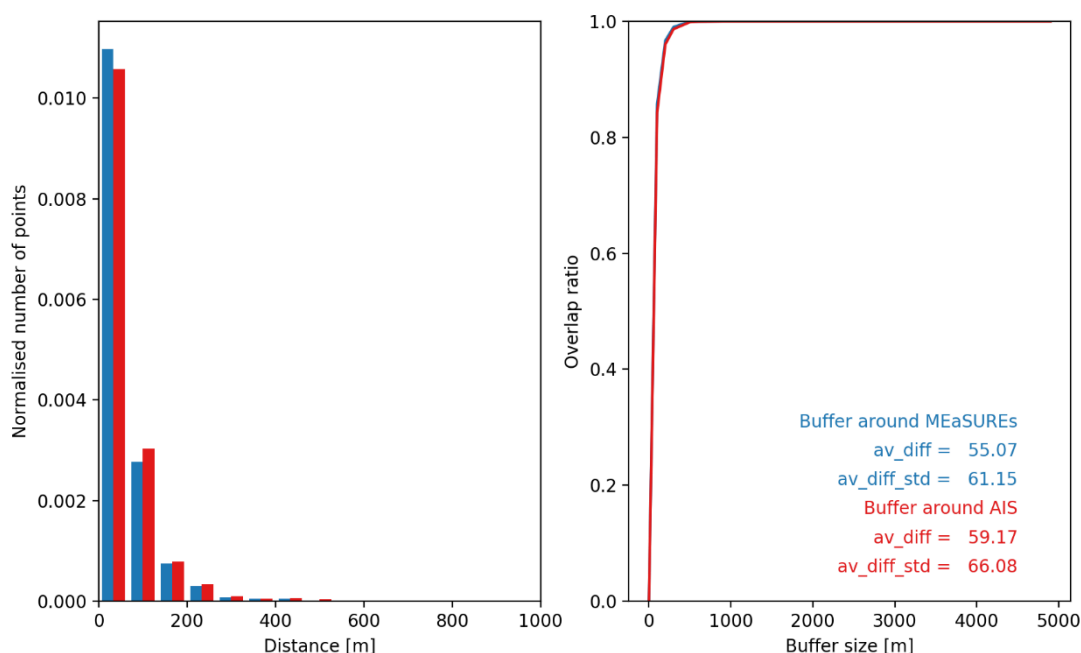


Figure 4-22: Same as Figure 4-21 (GLL has counterparts in both datasets) but for GLL segments generated from ERS-1.

4.3.8 Interpretation and explanation of validation outcome

Table 4-3 shows the mean distances of AIS_cci vs. ASAD, MOA and MEaSUREs for each investigated area as well as the overall average distances for each dataset (when all regions are included). In addition, the average distances were also determined without PIG area since we think the time series contained in PIG MEaSUREs dataset biases the result and makes it worse than it actually is. One has to bear in mind that ocean tides were not considered or corrected in any of the used datasets and shifts in GLL within one tidal cycle can reach up to 10 km if either tides are strong or the subglacial topography is gentle.

The comparison of all validation datasets reveals that MEaSUREs and AIS_cci match best, in average with 576 m which is an extremely good agreement. It was expectable though that results which utilize the same methodology would provide similar results. ASAD is the next best fit with an average distance of 1.2 km, while MOA's average distance is 1.8 km. The histograms itself enable a more detailed understanding of which accuracy bands are represented in which dataset to which extent.

Regarding the comparison of the AIS_cci GLLs processed from the same Sentinel-1A and ERS-1 datasets, the small values of the mean distances validate our products with respect to the MEaSUREs grounding line. Remaining differences can mostly be attributed to manual fringe delineation. The differences are however in a range that is to be expected and can be accepted for an indirect measurement of the GLL. A more thorough validation of the actual spatial accuracy of the GLL can only be achieved by comparing in situ measurements of the GLL.

Our machine-learning grounding-line delineations show median distances of 222 m and 265 m (Table 4-2) from the manual AIS_cci delineations. These offsets are slightly larger than the differences observed in the

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intercomparison between the MEaSUREs and AIS_cci manual products on the same dataset. Nevertheless, the achieved delineation accuracy is well within the expected range for an indirect measurement of the grounding-line location (GLL) and is therefore considered acceptable. This enables the AIS_cci grounding line pipeline to produce time-series spanning the entire Sentinel-1 time period without considerable manual mapping effort.

4.4 Recommendations for product improvement

There are currently no recommendations for product improvement.

4.5 Acknowledgements of data contributors for GLL validation

The following datasets were used for the present validation:

Haran, T., J. Bohlander, T. Scambos, T. Painter, and M. Fahnestock. 2005, updated 2013. MODIS Mosaic of Antarctica 2003-2004 (MOA2004) Image Map, Version 1. [Indicate subset used]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: <http://dx.doi.org/10.7265/N5ZK5DM5>. [Accessed February 2016].

Bindschadler, R., H. Choi, and ASAID Collaborators. 2011. High-resolution Image-derived Grounding and Hydrostatic Lines for the Antarctic Ice Sheet. Boulder, Colorado, USA: National Snow and Ice Data Center. <http://dx.doi.org/10.7265/N56T0JK2>.

Rignot, E., J. Mouginot, and B. Scheuchl. 2011b. Antarctic Grounding Line Mapping from Differential Satellite Radar Interferometry, *Geophysical Research Letters*. 38. L10504. <https://doi.org/10.1029/2011GL047109>

Rignot, E., J. Mouginot, and B. Scheuchl. 2016. *MEaSUREs Antarctic Grounding Line from Differential Satellite Radar Interferometry, Version 2*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: <http://dx.doi.org/10.5067/IKBWW4RYHF1Q>. [Accessed March 2017].

Scheuchl, B., J. Mouginot, E. Rignot, M. Morlighem, and A. Khazendar (2016), Grounding line retreat of Pope, Smith, and Kohler Glaciers, West Antarctica, measured with Sentinel-1a radar interferometry data, *Geophys. Res. Lett.*, 43, 8572–8579, doi:10.1002/2016GL069287.

Mohajerani Y, Jeong S, Scheuchl B, Velicogna I, Rignot E, Milillo P. Automatic delineation of glacier grounding lines in differential interferometric synthetic-aperture radar data using deep learning. *Sci Rep*. 2021;11(1):4992. Published 2021 Mar 2. doi:10.1038/s41598-021-84309-3

5 Gravimetric Mass Balance (GMB)

This chapter reports on the activities carried out to assess the quality of the GMB products. All assessments make use of the CCI+ Climate Research Data Package (CRDP) product version 5.2, which includes the gapfilling interpolation across the 11-months gap between GRACE and GRACE-FO. The product is being provided via the AIS_cci GMB data portal (data1.geo.tu-dresden.de/ais_gmb). The data package relies on the monthly solution series CSR RL06.3 provided by the Center for Space Research (University of Texas at Austin) (Bettadpur 2018) and covers the period 2002-04 – 2025-03. The utilised GRACE series CSR RL06.3 includes spherical harmonic coefficients up to degree $l_{max}=96$, although we only made use of the coefficients until degree 90. Figure 5-1 shows the mass balance pattern (i.e. the linear trend) derived from the entire time series of GRACE and GRACE-FO (both referred to as GRACE in the following).

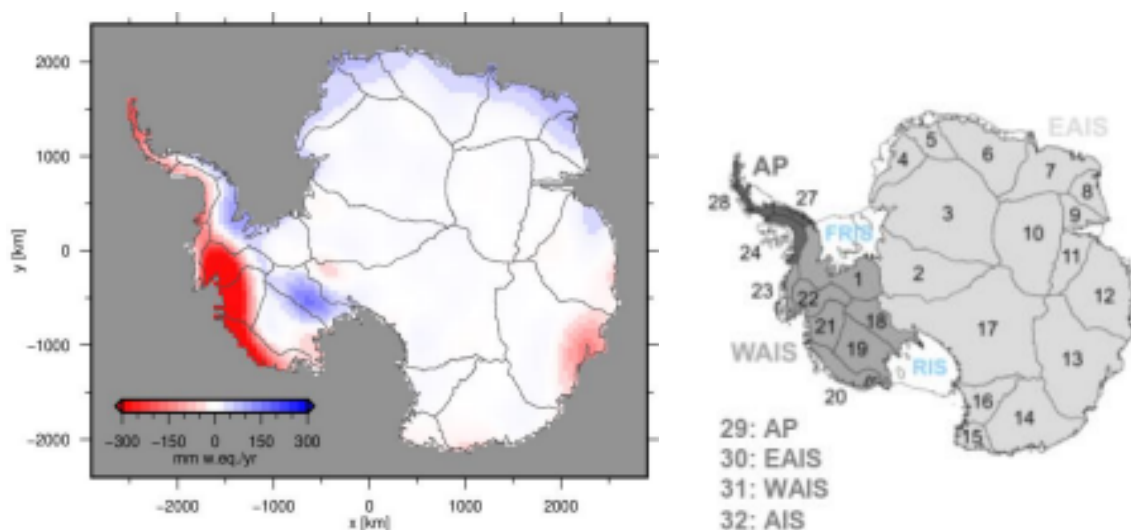


Figure 5-1: Left: Spatial pattern of the linear trend in ice mass during the period 2002-04 – 2025-03. Units are $\text{kg m}^{-2} \text{yr}^{-1}$, or mm water equivalent per year. Right: Basin numbers for later reference.

5.1 Independent validation data

5.1.1 Requirements

An ideal validation data set would consist of an independent observation of the quantity to be validated, carried out by an alternative sensor, which is more precise and provides an identical spatial coverage at higher spatial resolution. In case of the GMB data set the validation data are required to provide observations of the change in ice mass with a temporal resolution of one month and covering the entire AIS or large sub-regions like drainage basins.

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Unfortunately, no sensor except for GRACE is able to directly observe changes in mass with a comparable or even better spatial and temporal coverage. Hence, observations of alternative quantities related to mass changes have to be used after applying an appropriate conversion. For example, changes in the ice sheet's surface elevation can be converted into mass changes using an assumption of the density. The validation could also be based on the predictions of geophysical models. All these alternatives have the drawback of being dependent on additional assumptions and input data with their individual uncertainties.

5.1.2 Sources

Four major types of data sets are suitable for the GMB product validation. The following provides a brief description of the four data types. An inter-comparison of results based on these types of data as well as on GRACE/GRACE-FO satellite gravimetry is given by Otosaka et al. (2023a).

GRACE

GRACE data (either Level-1 observation data or Level-2 gravity field solution products) have been analysed for ice-sheet mass balance inferences by a number of research groups and by a variety of methods. These methods differ by the way how they account for uncertainties in the GRACE data and for effects of the limited spatial resolution (leakage errors) as well as by the geophysical corrections they apply. Comparisons between alternative GRACE-based ice-sheet mass balance estimates have therefore been essential to evaluate the results. It is understood that such comparisons are anything but a validation by independent datasets. Yet such comparisons are indispensable to understand, among other things, uncertainties of gravimetric mass balance products. Apart from the IMBIE assessments (Otosaka et al. 2023a), the AIS_cci Round Robin Experiment (Groh et al. 2019) was instrumental in this regard.

SEC

Surface elevation changes (SEC) of the AIS have been observed by different types of satellite altimetry missions, carrying radar instruments (e.g. Envisat, CryoSat-2) or laser instruments (ICESat, ICESat-2). Satellite altimetry allows the precise mapping of SEC patterns, where radar altimetry provides the longest record with a monthly temporal sampling. Shepherd et al. (2019) compiled a SEC time series spanning the period from 1992 to 2017 from cross-calibrated observations of the radar satellites ERS-1, ERS-2, ENVISAT and CryoSat-2.

Averaged over a certain drainage basin, volume changes need to be converted into mass changes in order to make them comparable to GMB products. Different approaches are used for this purpose. One approach makes use of a prescribed density model to discriminate between regions where fluctuations in elevation occur with the density of snow or ice (McMillan et al., 2014, Shepherd et al., 2019). Other studies make use of a firn compaction model (Ligtenberg et al., 2011) forced by a regional climate model (van Wessem et al., 2014) to correct SEC observations for fluctuations in the firn layer thickness.

SMB

Surface mass balance (SMB), defined as the difference between the mass gained by precipitation and the mass lost by sublimation and run-off, is one component of the ice sheets total mass balance (Otosaka et al., 2013b). Fluctuations in SMB can be predicted by regional climate models at high spatial (10-30 km) and temporal resolution (monthly) (Lenaerts et al., 2012), like the widely used model RACMO (van Dalum et al., 2024). For regions where the mass balance is dominated by changes in SMB, modelled cumulated SMB anomalies can be used for the inter-comparison with GMB time series. Even for regions where ice-dynamical

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imbalance prevails on the long term, interannual variations of ice mass are typically dominated by fluctuations in SMB. Therefore, the interannual component of ice-mass change time series can be validated by comparing de-trended time series of mass change with de-trended time series of the effect of SMB fluctuations.

IOM

The Input-output method (IOM) relies on the combination of mass input at the surface and mass loss through ice discharge into the ocean (Otosaka et al., 2013b). Information on the mass input is inferred from modelled SMB, while the mass discharge component is derived from ice velocity and ice thickness information. For example, yearly ice velocity estimates can be derived from interferometric synthetic-aperture radar data. Ice thickness may be derived by radar echo sounding or by using satellite altimetry in combination with the hydrostatic equilibrium of the floating ice shelves (Rignot et al., 2019). After interpolating the slowly change discharge estimates, monthly mass balance estimates can be derived on the scale of individual drainage basins or for the entire AIS.

5.1.3 Assessment

Each of the three non-GRACE data types introduced in the previous section comes with its individual strengths and weaknesses. For a comprehensive overview on the individual uncertainties cf. Otosaka et al., (2023a, 2023b) and references therein.

SEC observations may be biased by variations in the radar signal penetration into the firn layer. However, by far the largest uncertainties in SEC-based mass change time series arise from the conversion between volume and mass. Although the SEC patterns are provided at high spatial resolution, the polar gap prevents a complete coverage of the AIS.

Predicted fluctuations in SMB largely depend on the atmospheric forcing used as model input. Different global atmospheric reanalyses data sets used for SMB modelling yield significant differences in the model predictions (Mottram et al. 2021). Consequently, these uncertainties are propagated to derived products, like firn densification models used in SEC processing.

IOM results are very sensitive to uncertainties in both components, i.e. modelled fluctuations in SMB and observed ice velocity and thickness (Otosaka et al., 2013b).

5.1.4 Selection

Considering the limited number of possible data sets suitable for the GMB product validation and the limitations of each of these data sets, a comprehensive validation needs to be based on a variety of available sources. The following data sets are used in the GMB quality assessment:

GRACE. It is well established that the application of an identical methodology to different releases of state-of-the art GRACE L2 spherical-harmonic solutions yields results with very similar signal content, hence mass balance inferences (Jäggi et al., 2020, Ditmar et al. 2022). However, GMB results are sensitive to the applied methodology. We assess this sensitivity by: first, assessing our methodology through simulations; second, by comparing the CCI GMB product with results from the popular Level-1 based mascon solutions by NASA Jet Propulsion Laboratory (JPL) (Wiese et al., 2016; Watkins et al., 2015, https://podaac.jpl.nasa.gov/dataset/TELLUS_GRAC-GRFO_MAS_CON_CRI_GRID_RL06.3_V4), NASA Goddard Space Flight Center (GSFC) (Loomis et al., 2019, (<https://earth.gsfc.nasa.gov/geo/data/grace-mascons>)) and the Center for Space Research at the University of Texas at Austin (CSR) (Save et al., 2016, https://www2.csr.utexas.edu/grace/RL06_mascons.html). The mascon time series used here cover the time range from 2002-03 to 2023-10. Throughout the validation, we exclude two months (2017-03 and 2017-04)

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from the GMB products, as these months are outliers for a number of basins. (These months are still included in the delivered GMB products leaving the decision on their use to the users.)

SEC. A SEC-based mass change time series for different drainage basins and aggregations derived from radar altimetry observations were provided by Northumbria University. The conversion from volume to mass was achieved using the time-evolving density model according to Shepherd et al., (2019). This time series covers the period 1992-04 – 2023-10 and allows the inter-comparison with the corresponding time series from the GMB basin product (cf. PUG).

SMB. Monthly time series of basin-averaged cumulative SMB anomalies were derived from SMB predictions according to the newest version of the established regional climate model RACMO2.4p1 (van Dalum et al., 2024) with a spatial resolution of 27 km x 27 km. The time series used here covers the period between 1979 and 2022-12. At one instance, we consider two additional SMB predictions for the purpose of assessing the sensitivity of results to the SMB model choice. Hence, we additionally use output from the models MARv3.12 (Kittel et al. 2021) and GSFCv1.2.1 (Medley et al. 2022).

IOM. Published datasets on IOM results are available as mean linear trends over multi year time intervals (Rignot et al. 2019). Differences between IOM results by (Rignot et al. 2019) and results from the altimetry method and the gravimetry method on the level of long-term trends are well documented, e.g., by Otosaka et al. (2023a). Adjusting the long-term trends from IOM and GRACE to the same values, Velicogna et al. (2020) limits the subsequent comparison to a comparison of the interannual signal content. Interannual variations of IOM results are mainly due to interannual variations of SMB and are therefore addressed by SMB models. For these reasons, we do not include IOM results in the GMB validation.

5.2 Validation procedure

The conducted tests and inter-comparisons are based on long-term rates of mass change and the interannual component of mass variations. The long-term rate (i.e., the linear trend) is derived by fitting a linear and periodic (1 year, 1/2 year) model to the common period of the time series to be compared. The interannual component is derived by subtracting the fitted linear and seasonal model and subsequently smoothing the time series in the temporal domain by a Gaussian filter with a two-sigma width of 0.5 years.

GRACE methodology assessment: The utilized algorithm (Groh & Horwath, 2021) is applied to a range of synthetic data sets with a priori known mass changes. By comparing the derived mass change estimates with the true mass changes, conclusion on the performance of the algorithm and induced signal leakage can be drawn. The synthetic data sets used are identical to those utilized for the Round Robin experiment (Groh et al., 2019).

GRACE comparison with mascon products: Mass change time series for the entire AIS are compared w.r.t. their mean long-term rate of mass change and their interannual component.

SEC: Mass change time series for all drainage basins and their aggregations (AP, WAIS, EAIS, AIS) are compared w.r.t. their mean long-term rate of mass change and their interannual component. For the SEC time series, the temporal smoothing (employed otherwise in the derivation of the interannual component) is not done since the SEC mass time change time series have already been temporally smoothed. Correlation coefficients between the interannual components of GMB and SEC are calculated to assess agreement.

SMB: Since the basin-averaged accumulated SMB anomaly time series solely represent the surface component of the total mass change, a direct comparison to the GMB basin product is not possible. Ice discharge shows only negligible seasonal variations and is clearly dominated by long-term signals. To ensure comparability, long-term and seasonal signals are removed from both the SMB and the GMB time series

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through a functional fit as explained above. The residual interannual variations are mainly due to fluctuations in SMB. Correlations between the interannual variations from both time series are used as indicators for the level of agreement.

Assessment of GRACE–GRACE-FO continuity. The 11-month gap between GRACE and GRACE-FO frequently raises the question on biases between the mass balance results across this inter-mission gap. Indeed, for other Earth observation missions, say, e.g. for satellite altimetry, instrument effects may induce offsets between, say, the measured global mean surface heights as derived from different missions. For GRACE-like satellite gravimetry missions, while instrument calibrations are of course required and performed, any calibration issues cannot translate into a bias of the global mean of the GRACE results. The reason is that the GRACE data processing assumes and enforces global mass conservation. GRACE results address mass redistribution across the globe with zero mass change in the global integral. What GRACE instrument calibration issues could cause are differences in patterns of errors (in space and time) between the GRACE period and the GRACE-FO period. Landerer et al. (2020) analyse the GRACE/GRACE-FO continuity for a number of continental hydrological regions by utilizing hydrology models. They conclude that the GRACE/GRACE-FO observations "are consistent with independent mass change estimates, providing high confidence that no intermission biases exist from GRACE to GRACE-FO". Chang et al. (2021) speculate that a non-closure of the global sea-level budget after 2016 "might be derived from the inconsistency between GRACE and GRACE-FO". However, they do not address the fundamentally different effect that "data inconsistencies" in GRACE could have compared to "data inconsistencies" from other remote sensing missions. They also do not differentiate between the effect of trend differences across the whole GRACE/GRACE-FO period and actual offsets between results in these two periods. In the meantime, Barnoud et al. (2021) explain the bulk of the observed sea-level budget inconsistencies by biases in the underlying Argo float and satellite altimetry data sets.

We investigate the hypothesis of biases between GRACE and GRACE-FO results for the AIS GMB product. We subtract modelled interannual mass variations (based on different SMB models from the GMB time series. The resulting time series ("GMB minus SMB"), which show a long-term coherent behaviour overlaid by month-to-month noise is then used to fit a functional model to a time interval surrounding the GRACE/GRACE-FO gap. This fit is repeated by varying the functional model (linear or quadratic, including or excluding a seasonal component) and by varying the support interval length at both sides of the gap (e.g. 4 years or 5 years). An offset between the GRACE and GRACE-FO period is co-estimated with the other parameters of the functional model. The values estimated for this offset are then evaluated in the light of their formal uncertainties and of their spread across the different variants of the functional model fit and of the SMB correction in "GRACE minus SMB".

5.3 Validation outcome

GRACE methodology assessment:

The overall performance of the applied algorithm was demonstrated in the Round Robin experiment (Groh et al., 2019). The algorithm has been regularly updated since in order to find the optimal compromise between the minimisation of both GRACE/GRACE-FO error effects and signal leakage (Groh & Horwath, 2021). Such an update has been performed with any update of the GRACE/GRACE-FO input Level-2 solutions, most recently with the transition from CSR RL6.2 to CSR RL6.3. The updated synthetic results for the entire AIS are given in Figure 5-2. For example, the leakage error induced by the spatial pattern of the mean annual mass change of the AIS (data set number 7 – "AIS MB") is 1.2 Gt.

GRACE comparison with mascon products: The comparison between the three mascon time series and the AIS_cci+ GMB time series for the entire AIS is shown in Fig. 5-3. Over the common period, trends of the JPL, GSFC, and CSR mascon time series range between -128 and -144 Gt/yr. The AIS_cci+ GMB trend is -92 ± 44 Gt/yr. The main reason for this trend difference is in the GIA model employed for the GIA correction. The mascon solutions use the ICE-6G_D model (Peltier et al. 2015, 2018), while the GMB product uses the IJ05_R2 model (Ivins et al. 2013). Figure 5.2 also shows a variant of the GMB product where the ICE-6G_D model is applied for GIA correction (bold black curve). This renders the AIS trend more negative by 31 Gt/yr and brings the GMB trend close to the GSFC mascon trend at -125 ± 44 Gt/yr. Hence, the trend differences with the mascon solutions reflects the GIA uncertainty, which makes up the largest contribution to the assessed ± 44 Gt/yr trend uncertainty (Groh and Horwath, 2021).

Apart from the long-term linear trend, the GMB solutions agrees with the mascon solutions on interannual time scales. This is illustrated in Figure 5-4. Increase spread among the solutions close to the end of the GRACE life time are associated to larger noise together with edge effects of the temporal smoothing close to the data gap.

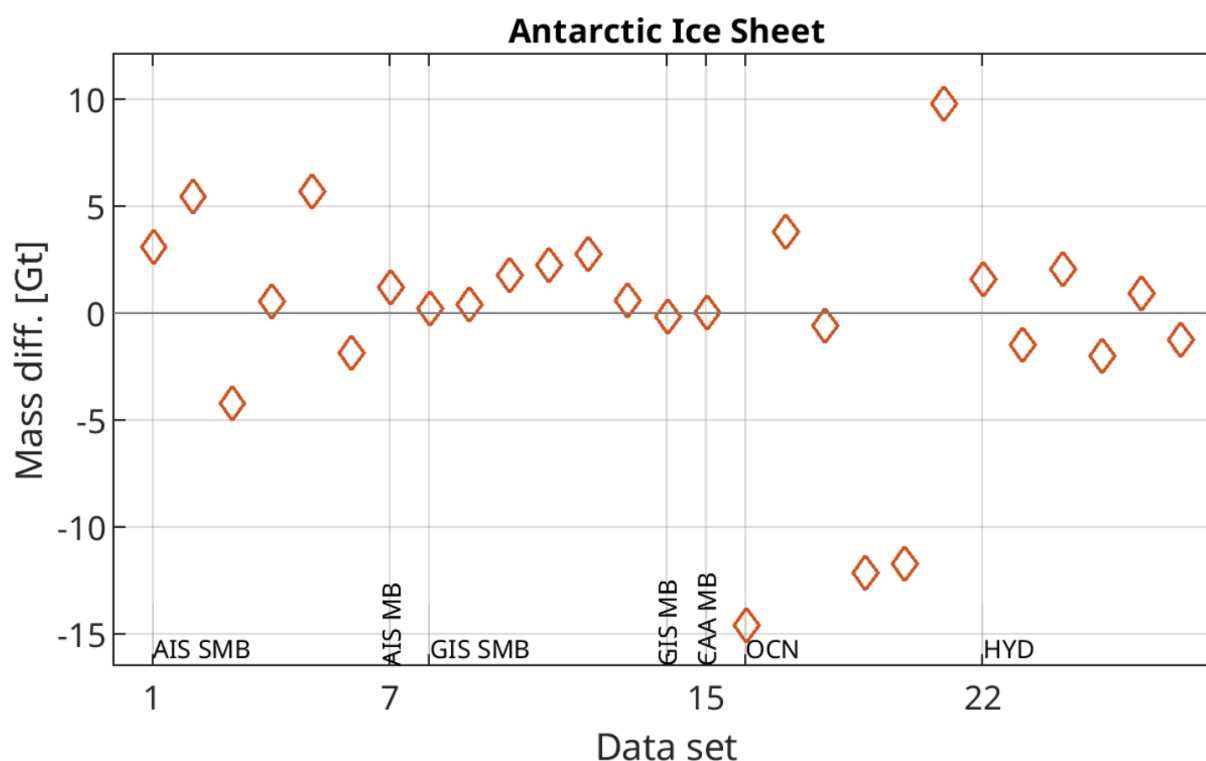


Figure 5-2: Leakage assessment, shown for the example of the entire AIS: Differences between the mass changes derived from synthetic data sets and the corresponding synthetic 'true' mass change. The bottom row indicates the type of synthetic data sets according to the description by Groh and Horwath (2021), which include signals due to AIS SMB variability ('AIS SMB'), AIS mass total mass trends ('AIS MAB'), Greenland Ice Sheet mass changes ('GIS SMB', 'GIS MB'), global oceanic mass changes ('OCN') and hydrological mass changes ('HYD').

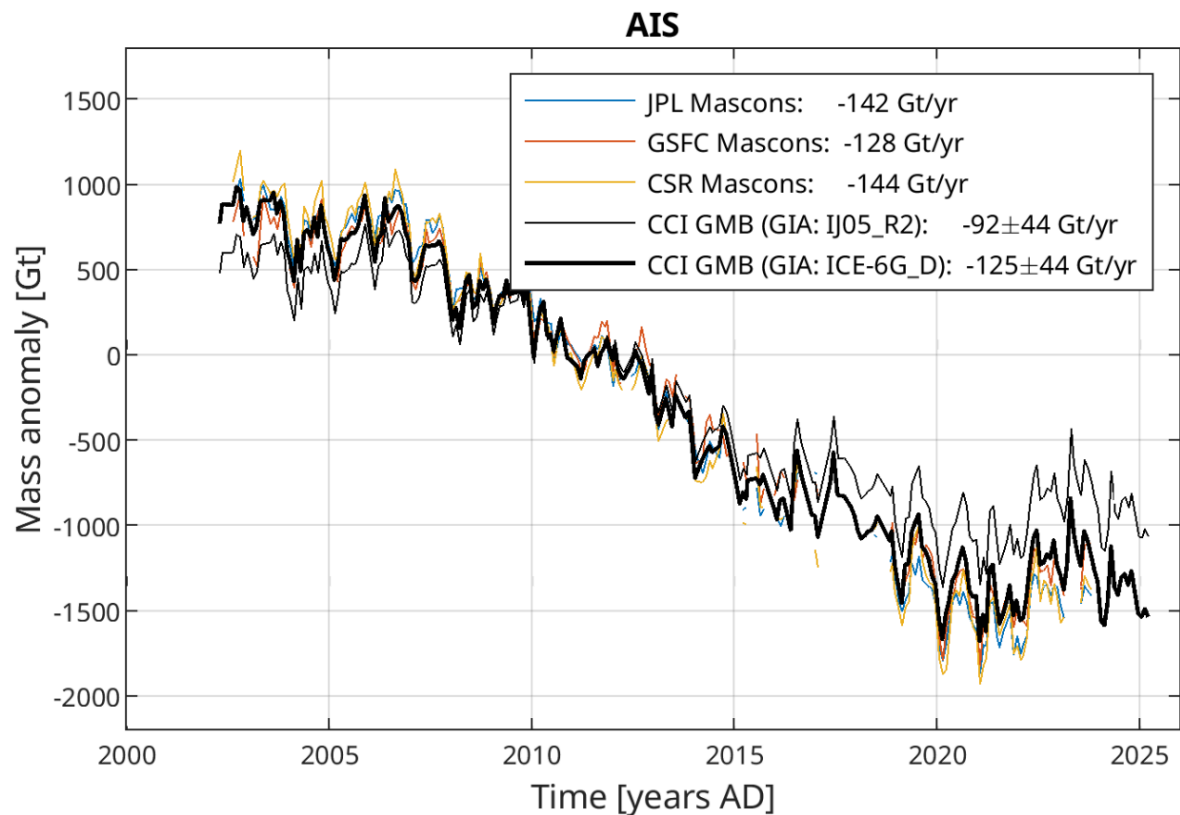
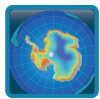


Figure 5-3: Mass change time series for the AIS according to the mascon solutions by JPL, GSFC and CSR, the CCI GMB product, and a variant of the CCI GMB product using ICE-6G_D instead of IJ05_R2 for the GIA correction. Linear trends over the common period are quoted in the legend.

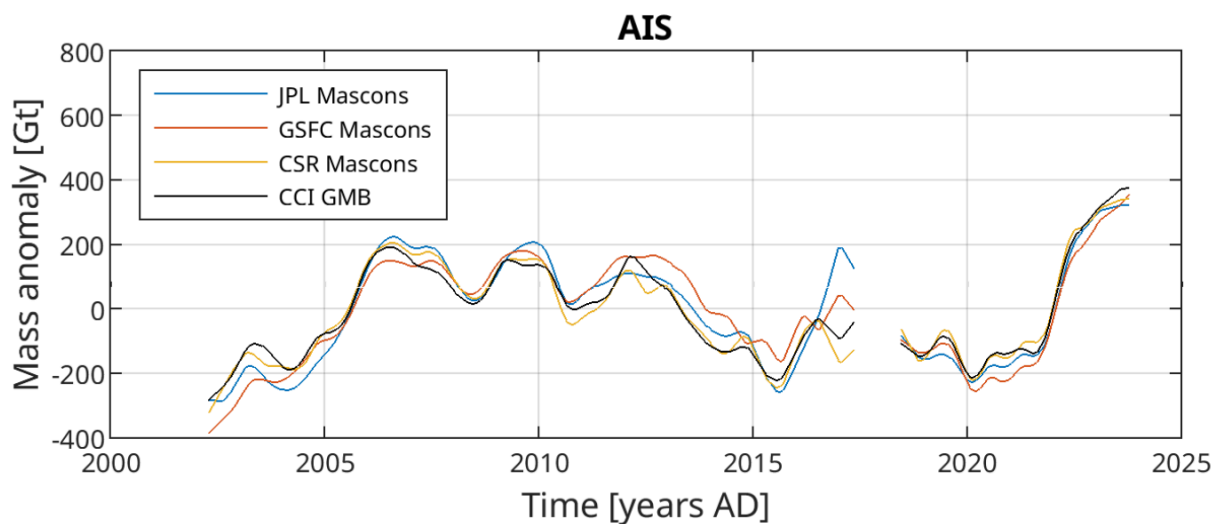


Figure 5-4: Interannual component of mass changes according to the same products as in Fig. 5-3.

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SEC: Figure 5-5 illustrates the comparison of time series from GMB and SEC. Both the full time series and the interannual components (dashed lines) are shown. Table 5-1 provides statistics on the comparison in its columns 2 to 5. For the entire AIS the linear trends over the common period (2002-04 - 2023-10) are -91.6 ± 44 Gt/yr for GMB and -111.7 Gt/yr for SEC (see Table 5-1 last line and Fig. 5-5 last subplot) and hence agree within GMB uncertainties. The situation is different for sub-regions. The GMB trend is 23 Gt/yr more negative, 59 Gt/yr more positive, and 15 Gt/yr more negative than the SEC-based estimate for the WAIS, the EAIS and the AP. These differences are beyond the one-sigma trend uncertainties assessed for GMB. They resemble differences found in more comprehensive inter-comparisons (Otosaka et al. 2023a). Accordingly, the agreement of trends on the drainage basin level varies. There is, however, agreement on the sign of the trend for all basins except for three basins (Basins 10, 14, 19 – see Fig. 5-1 for basin definitions), with insignificant GMB trends. Comparisons of the interannual components (dashed lines in Fig. 5-5, correlations in Table 5-1, Column 5) shows that both datasets reflect common interannual signal, where visual inspection of the SEC curves suggests a stronger smoothing in this representation. The median of the correlation coefficients over all basins is 64%

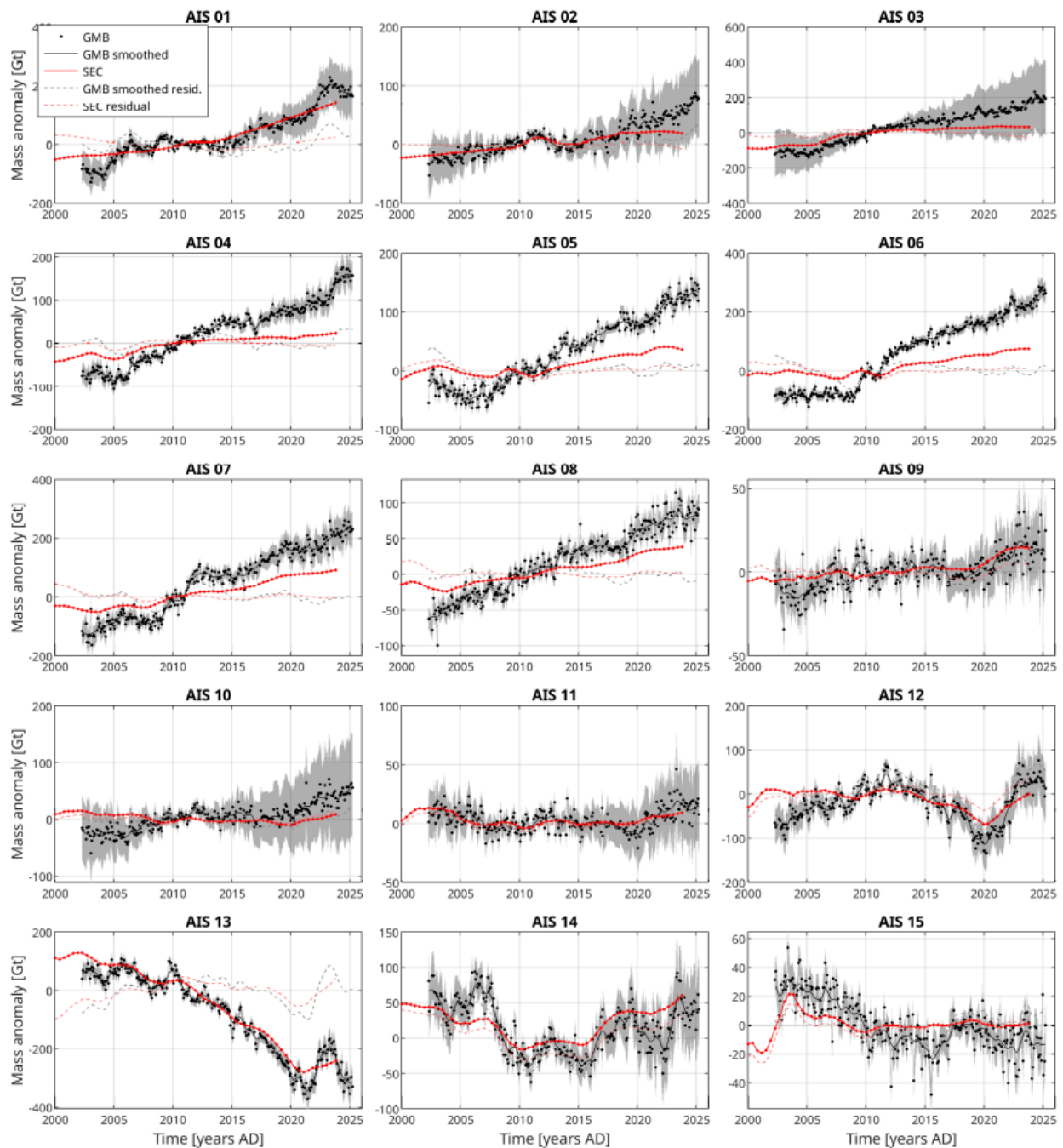
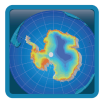


Figure 5-5: Comparison of time series from GMB and SEC for each drainage basin (1-27, see headers and see Fig. 5-1 for basin definitions) and for aggregated basins (29-32). GMB time series (black) with error bars (grey-shaded) that combine the effect of the trend uncertainty and the uncorrelated noise; SEC (red); interannual components of GMB (grey dashed) and SEC (red dashed). Ordinate scales differ. The figure is continued on the next page

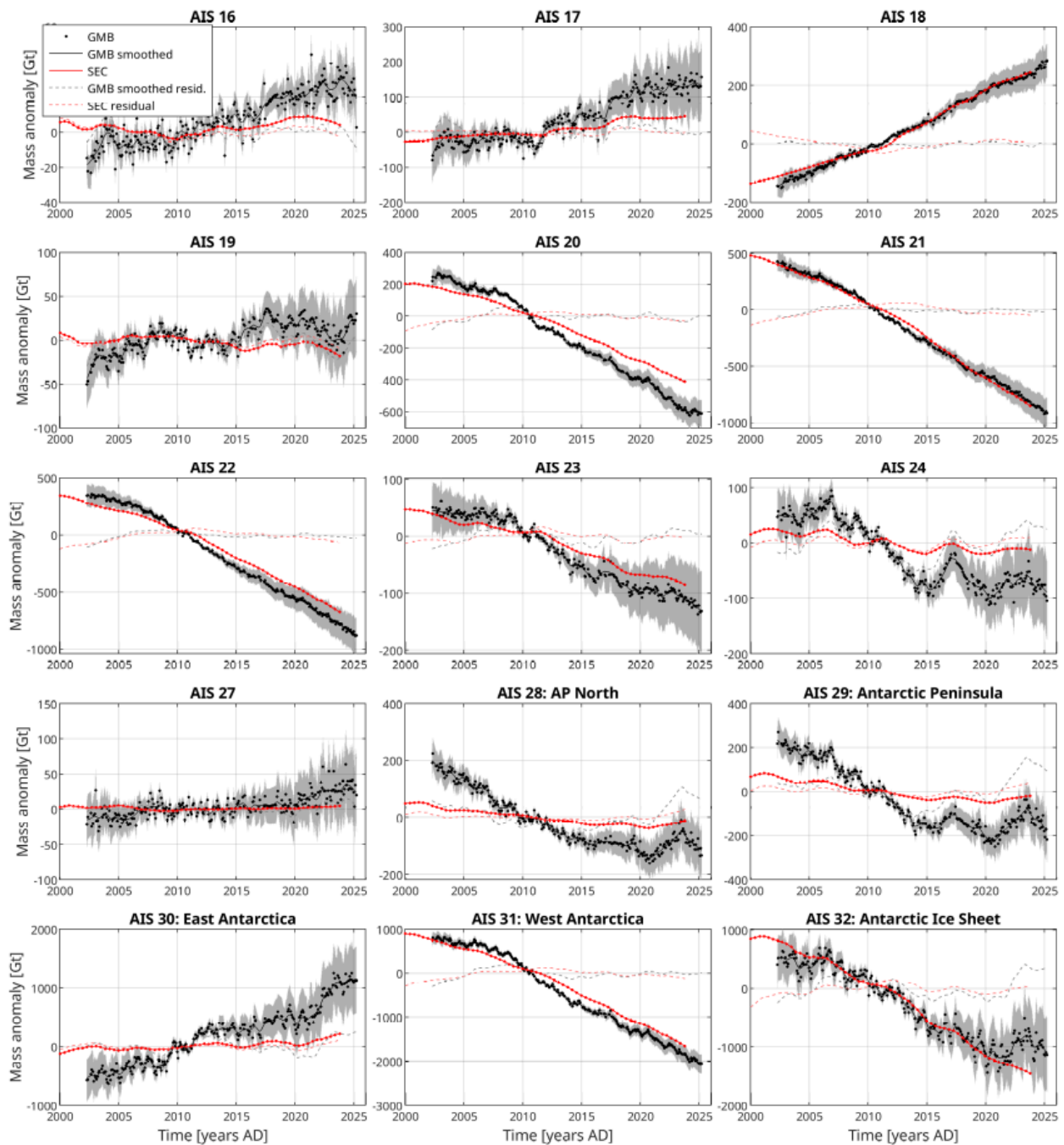


Figure 5-5: continued

Table 5-1: Statistics on the inter-comparison of GMB basin products with SEC-based and SMB-based mass variation time series. Each line is for one basin or basin aggregation (see Fig. 5-1 for basin definitions). Column (1): Basin number; (2): GMB linear trend for the time period overlapping with SEC; (3) uncertainty of linear trend as stated for GMB product; (4) SEC linear trend; (5): Correlation between interannual components of GMB and SEC time series; (6) Correlation between interannual components of GMB and cumulated SMB anomaly time series; (7) GMB noise components as stated for the GMB product; (8): RMS of the difference of the unsmoothed interannual component of GMB and the interannual component of cumulated SMB anomalies. See main text for more explanation.

1	2	3	4	5	6	7	8
Basin ID	Linear trend GMB [Gt/yr]	Uncertainty of linear trend GMB [Gt/yr]	Linear trend SEC [Gt/yr]	Correlation interannual GMB vs SEC [%]	Correlation interannual GMB vs SMB [%]	GMB noise [Gt]	RMS detrended GMB minus detrended SMB [Gt]
1	10.5	5.9	8.4	42	80	10.5	14.1
2	3.4	4.7	2.1	50	63	8.4	9.8
3	13.7	14.9	5.6	76	90	13.4	13.2
4	9.5	2.4	2.6	78	88	8.0	9.0
5	8.4	0.9	2.2	77	91	9.7	11.3
6	17.4	2.3	4.6	55	95	11.7	12.8
7	16.4	3.9	7.1	58	91	18.3	18.5
8	6.6	1.1	2.9	7	72	11.3	11.5
9	1.0	1.4	0.7	39	78	6.5	7.3
10	2.7	6.4	-0.6	14	84	9.9	9.4
11	-0.0	2.3	-0.1	69	69	6.5	6.5
12	-0.6	4.2	-2.6	89	97	14.8	14.9
13	-19.8	2.9	-20.6	89	95	16.5	18.7
14	-1.8	3.7	0.7	87	95	14.6	15.0
15	-1.9	0.7	-0.5	61	90	9.3	10.0
16	1.9	0.9	0.4	67	69	5.3	5.8
17	9.4	7.0	3.3	80	93	16.8	17.1
18	18.4	4.0	17.6	74	59	6.0	6.3
19	1.7	3.0	-0.5	49	92	5.6	6.2
20	-41.4	5.9	-28.4	58	57	7.7	8.3
21	-60.6	9.2	-60.0	54	46	9.7	10.4
22	-57.3	11.1	-45.4	69	64	9.0	11.8
23	-8.8	5.0	-6.0	51	90	5.6	6.5
24	-8.0	4.9	-1.9	75	91	8.7	11.0
27	1.5	3.6	0.0	-2	13	8.9	10.7
28	-13.9	5.9	-3.3	85	86	12.3	15.2
29 (APIS)	-20.4	7.2	-5.1	92	95	18.7	22.2
30 (EAIS)	66.2	39.7	7.7	67	93	70.6	67.6
31 (WAIS)	-137.5	15.0	-114.3	50	68	26.8	29.1
32 (AIS)	-91.6	44.0	-111.7	59	72	87.6	90.0

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SMB: Figure 5-6 illustrates the comparison between GMB and the mass variations due to SMB variations. While curves prior to detrending are shown as context, the main comparison is on the interannual components (bold lines). The interannual signal in GMB consistently reflects SMB-induced variations, including effects of excess snowfall events, e.g. in 2009 and 2011 (Basin 6, 7) or in 2020-2023 (Basins 12-14). Differences between the curves for the Thwaites Glacier and Pine Island Glacier basins (Basins 21, 22) as well as for the entire WAIS and AIS (Basin 31 and 32) also reflect non-linear mass changes (acceleration of mass loss) due to changing ice-flow dynamics. Correlations between the GMB and SMB interannual signals, as given in Table 5-1 (column 6), are high, with a median value at 87%

We also use the GMB-versus-SMB comparison to validate the assessment of the month-to-month noise content of the GMB product (quoted in Table 5-1 column 7). For this purpose, we calculate the RMS difference between detrended (but unfiltered) GMB time series and the detrended SMB time series. In this analysis, we consider a quadratic term in addition to the linear and periodic terms in the mathematical model used to fit and subtract the trend, in order to reduce the bulk of non-linear dynamically induced changes from the GMB signal. The GMB-minus-SMB RMS values thus obtained are given in Table 5-1 last column. They are close to the assessed noise level. More precisely, RMS difference (GMB-minus-SMB) is somewhat larger than the assessed noise level (with a median ratio at 1.09), which may be due to residual signal in the GMB-SMB difference time series.

Assessment of GRACE–GRACE-FO continuity.

Figure 5-7 exemplifies the procedure of tentatively estimating offsets between the GRACE and GRACE-FO. For the case of the entire AIS time series, six variants of the estimate are shown. They differ by the SMB model employed to calculate "GMB minus SMB" (grey lines) in subplot a, b, and c. The functional model illustrated here is a linear model with identical slope during the GRACE and GRACE-FO period but with an offset during the inter-mission gap. The model is fit to two alternative intervals spanning 4 years (red line) and 5 years (blue line), respectively, at both sides of the inter-mission gap. The figure illustrates that the estimated offsets are small and vary across the six variants shown. This indicates that any estimated offset mainly reflects noise in the GMB time series and errors in the subtracted SMB model results, apart from possible true non-linearities in the dynamically induced mass changes. Hence, the estimated offsets are not indicative of any biases between the GMB results from GRACE and GRACE-FO.

Figure 5-8 shows the results of the offset estimate for each drainage basin as well as for their aggregations (including the entire AIS as basin number 32). The results are not unequivocal neither across basins nor across estimation variants for individual basins. This is particularly apparent for the entire AIS, where offset estimates are insignificant given their uncertainties and sensitive to the choice among the six variants. The sensitivity of the offset estimates to variations of the parametrisation (inclusion of seasonal terms and of a quadratic term) is relatively small (not shown here). In conclusion, the estimates are not indicative of any biases between the GMB results from GRACE and GRACE-FO. This confirms an unbiased GRACE–GRACE-FO continuity

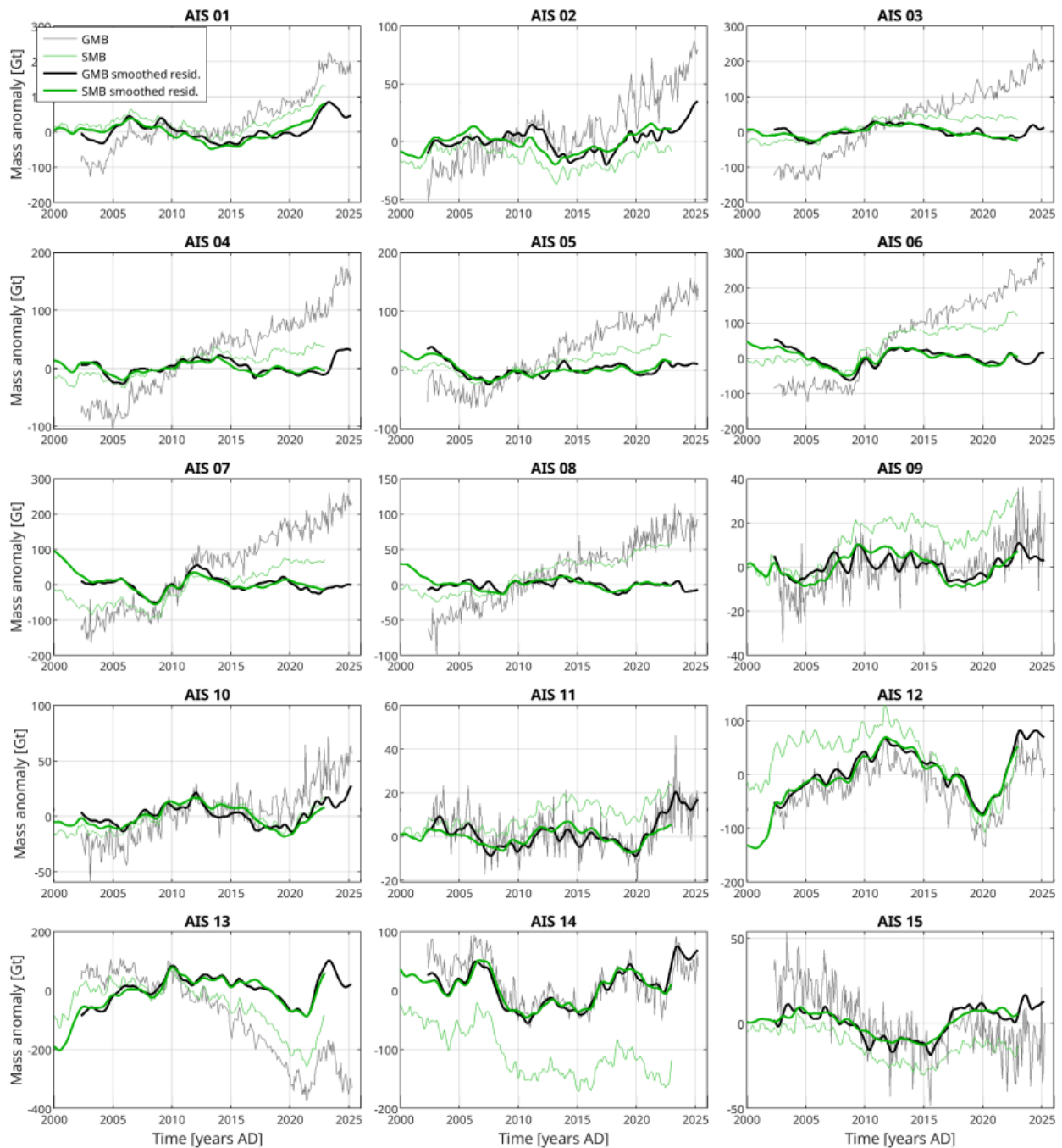
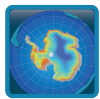


Figure 5-6: Comparison between GMB and cumulated SMB anomalies (cSMBA) for each drainage basin (1-27, see headers and see Fig. 5-1 for basin definitions) and for aggregated basins (29-32). Original GMB basin product (gray) and cSMBA time series (light green); interannual component of GMB product (bold black) and cSMBA (bold green). Ordinate axis scales differ. The figure is continued on the next page.

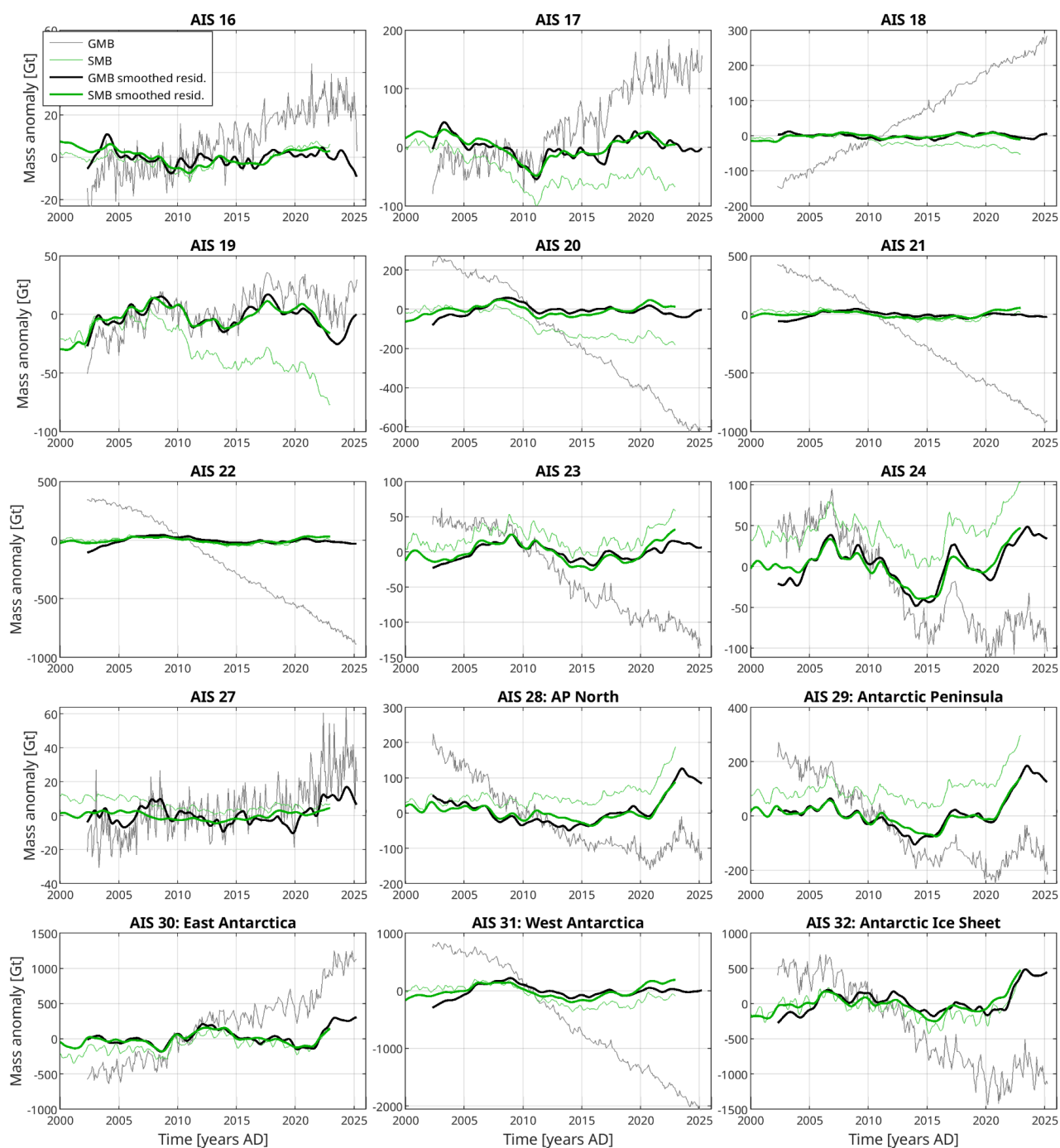


Figure 5-6: continued

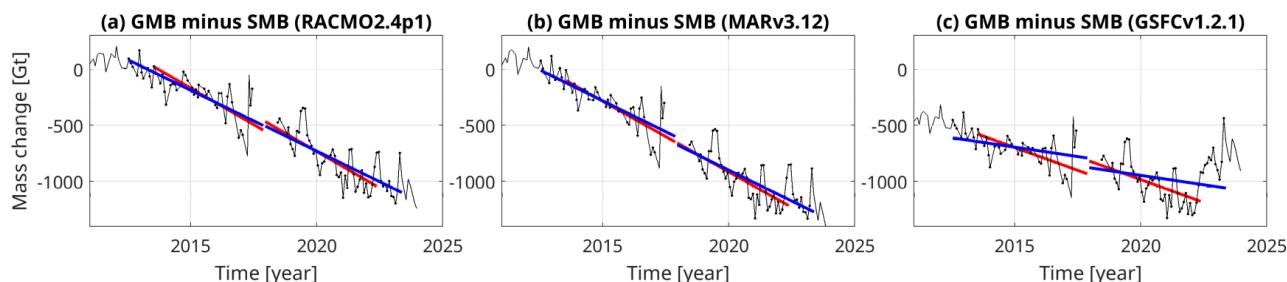


Figure 5-7: Illustration of the tentative estimation of offsets between the GMB mass anomalies over the GRACE and GRACE-FO periods. Grey curves: time series of GMB minus SMB (more precisely: GMB minus the effect of SMB fluctuations on GMB) based on three different SMB models: (a) RACMO2.4p1 (van Dalum et al. 2024) (b) MARv3.12 (Kittel et al. 2021) (c) GSFCv1.2.1 (Medley et al. 2022). Straight lines: functional fit (linear function with an offset in the inter-mission gap) adjusted to 4 years (red) or 5 years (blue) prior to and after the inter-mission gap. The offsets between the curves prior to and after the gap are the target parameter of this investigation. These offsets are small compared to the mass change signal and they are not robust against the choice among the six variants shown here.

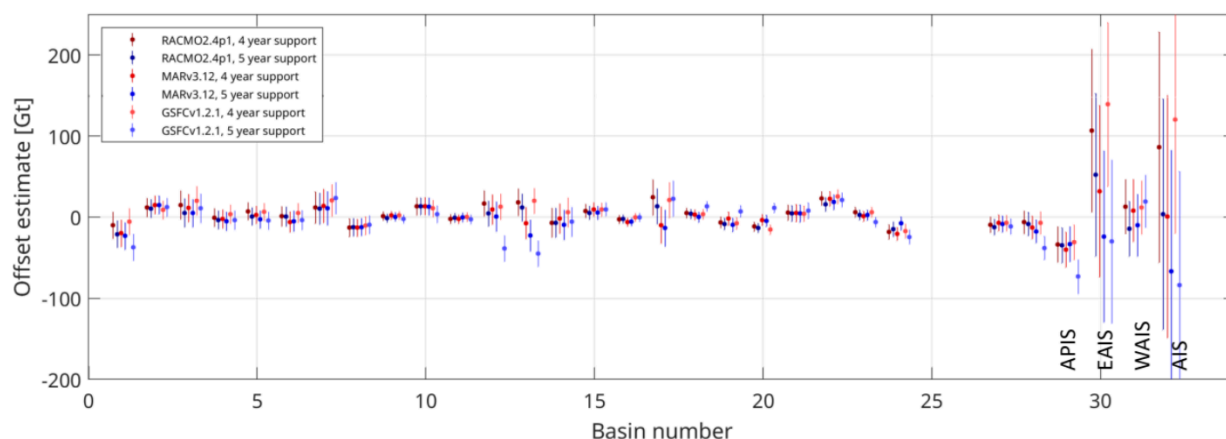


Figure 5-8: Tentative estimates of offsets between the GRACE and GRACE-FO GMB products shown for every basin (indicated by basin number) and the aggregations Antarctic Peninsula (APIS), East Antarctic Ice Sheet (EAIS), West Antarctic Ice Sheet (WAIS) and entire Antarctic Ice Sheet (AIS). For each basin, six variants are shown together with their formal one-sigma error bars. The six variants differ by their employed SMB models and underlying support intervals, as shown in the legend and illustrated in Fig. 5-7. There are no coherent offsets across the basins. In particular, for entire AIS, offset estimates are insignificant given their uncertainties and sensitive to the choice among the six variants.

5.4 Recommendations for product improvement

The development of Level-2 gravity field products needs to be followed so that the choice of the input to the GMB analysis can benefit from the best gravity field processing.

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The gap filling interpolation performed during AIS_cci+ phase two may be generalized to filling the several one-month gaps within the GRACE and GRACE-FO mission lifetimes.

More generally, the development should lead to a reconsideration and improvement of the temporal representation of mass changes by the GMB products. The current GMB products consist of monthly mass anomalies $\Delta m(t)$ (with respect to an arbitrarily chosen reference time), and the associated uncertainties. We also provide a mean rate of mass change over the entire interval covered by the time series. However, currently it is up to users to derive mass balance, expressed in rates of mass change, $dm/dt(t)$, in their temporal resolution of interest. Also, we do not currently provide information on the significance of mass changes - both in terms of statistical significance and in terms of significance as a climate signal. It is recommended, in a next phase, to evaluate time-variable $dm/dt(t)$, and use the results to provide indicators of change.

5.5 Acknowledgements of data contributors for GMB validation

We acknowledge the support by Northumbria University and the Institute for Marine and Atmospheric Research Utrecht (IMAU) who provided SEC-based mass change time series and fluctuations in SMB predicted by RACMO2.4, respectively.

6 Ice Shelf Coast Line (ISCL)

NOTE: This section of the ADP was written as a result of CCN1 of ESA contract number 4000143397/23/I-NB.

This chapter outlines the activities undertaken to evaluate the quality of the Ice Shelf Coast Line (ISCL) products developed in AIS CCI+ Option 1. The intercomparison/validation efforts presented here focus on the monthly ISCL products generated from Sentinel-1 (S1) SAR data. The validation dataset encompasses three major Antarctic ice shelves: Larsen-C (Antarctic Peninsula), Filchner, and Ronne (further divided into Ronne 1 and Ronne 2). The delineation of the ISCL is performed by first using elevation data from CryoSat-2 altimetry tracks to provide an initial estimate of the coastline based on elevation differences, which, together with corresponding S1 imagery, is input into a Convolutional Neural Network (CNN) that combines both data sources to produce a preliminary ISCL prediction, followed by iterative refinement through the model until the predicted coastline converges. The ISCL datasets are provided monthly for each ice shelf from January 2018 to December 2021 as GeoPackage (GPKG) shapefiles containing LineString geometries. The validation performed here intercompares the ISCL dataset with a dataset of manually delineated ice front positions using Sentinel-1 imagery as described in section 6.1 following the procedures described in section 6.2. The validation outcome is provided in section 6.3. Recommendations for future development are provided in section 6.4.

6.1 Independent validation data

For the validation of the ISCL products, Ground Range Detected (GRD) S1 images acquired in Extra Wide (EW) swath mode were used to guarantee full coverage of the ice shelves in a single acquisition. Only January products were selected for validation, providing one validation per year for each ice shelf. Table 6.1 lists the S1 products used in the validation.

Ice Shelf	Sentinel-1 Product	Date
Filchner	S1A_EW_GRDM_1SSH_20180115T012511_20180115T012615_020158_022626_F5BC.SAFE	2018/01/15
Filchner	S1A_EW_GRDM_1SSH_20190101T014946_20190101T015051_025277_02CBB1_FE3B.SAFE	2019/01/01
Filchner	S1A_EW_GRDM_1SSH_20200117T012524_20200117T012628_030833_03899F_7145.SAFE	2020/01/17
Filchner	S1A_EW_GRDM_1SSH_20210118T011721_20210118T011826_036185_043E38_736F.SAFE	2021/01/18

Larsen-C	S1A_EW_GRDM_1SSH_20180118T001459_20180118T001559_020201_022779_1B12.SAFE	2018/01/18
Larsen-C	S1A_EW_GRDM_1SSH_20190113T001506_20190113T001606_025451_02D1F0_32A3.SAFE	2019/01/13
Larsen-C	S1A_EW_GRDM_1SSH_20200108T001513_20200108T001613_030701_0384F0_1EA9.SAFE	2020/01/08
Larsen-C	S1A_EW_GRDM_1SSH_20210119T002324_20210119T002424_036199_043EBD_FC86.SAFE	2021/01/19
Ronne 1	S1A_EW_GRDM_1SSH_20180111T015840_20180111T015949_020100_02244F_1284.SAFE	2018/01/11
Ronne 1	S1A_EW_GRDM_1SSH_20190118T015847_20190118T015956_025525_02D4A6_E1AC.SAFE	2019/01/18
Ronne 1	S1A_EW_GRDM_1SSH_20200114T010200_20200114T010312_030789_038807_1F82.SAFE	2020/01/14
Ronne 1	S1A_EW_GRDM_1SSH_20210107T015859_20210107T020008_036025_04389E_FF05.SAFE	2021/01/07
Ronne 2	S1A_EW_GRDM_1SSH_20180111T015840_20180111T015949_020100_02244F_1284.SAFE	2018/01/11
Ronne 2	S1A_EW_GRDM_1SSH_20190118T015847_20190118T015956_025525_02D4A6_E1AC.SAFE	2019/01/18
Ronne 2	S1A_EW_GRDM_1SSH_20200114T010200_20200114T010312_030789_038807_1F82.SAFE	2020/01/14
Ronne 2	S1A_EW_GRDM_1SSH_20210107T015859_20210107T020008_036025_04389E_FF05.SAFE	2021/01/07

Table 6.1: List of Sentinel-1 acquisitions used for the validation of ISCL products

6.2 Validation Procedure

For each monthly product, the validation was conducted following the procedure outlined below:

1. Manual delineation of the calving front in QGIS, using the corresponding Sentinel-1 imagery for the selected month.
2. Discretization of the calving front line by generating one point every 100 meters.
3. Computation of distances between each point in the reference and validation datasets, using the shortest line.
4. Calculation of statistical indicators, including:
 - a. Number of points
 - b. Mean distance [m]
 - c. RMSE: Root Mean Square Error [m]
 - d. STD: Standard Deviation [m]
 - e. Median distance [m]
 - f. MAD: Mean Absolute Deviation [m]
 - g. Percentage of distances below 100 meters
 - h. Percentage of distances below 1 kilometer
 - i. Distance distribution (histogram)

Note: During the manual delineation process, it was observed that rifts and other types of cracks within the ice shelf were not identified as part of the coastline. This resulted in abnormally large distance discrepancies between the manually delineated and ISCL datasets. To prevent bias from these extreme values, the corresponding distance measurements were excluded from the statistical analysis. Furthermore, since some calving front products do not cover the entire ice shelf coastline, distances calculated in the uncovered regions were also omitted from the study (Figures 6.1 and 6.2).

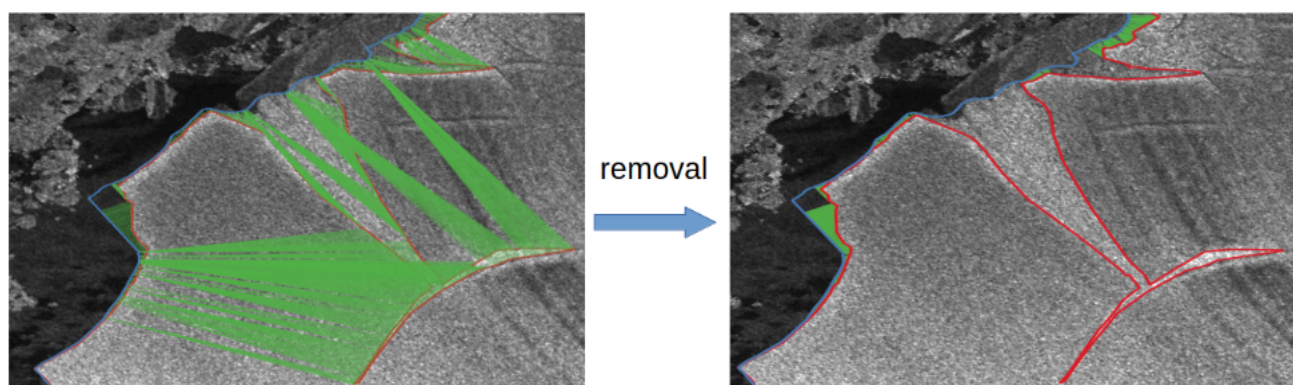


Figure 6.1: Example of a removal of the shortest distances in rifts, between reference (red) and validation ISCL (blue), for Filchner Ice Shelf, in January 2020

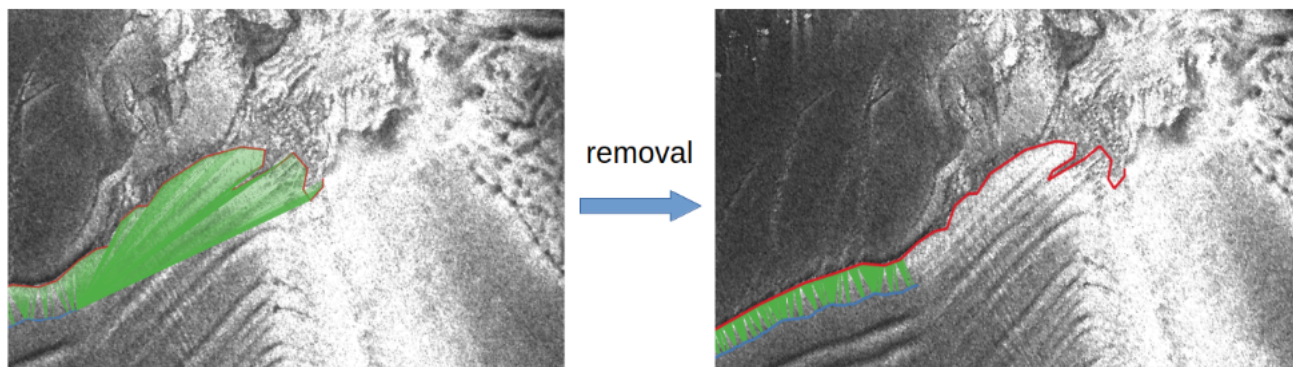


Figure 6.2: Example of a removal of the shortest distances, between reference (red) and validation ISCL (blue) computed in the east side of Filchner Ice Shelf (January 2020)

6.3 Validation Outcome

This section presents the results of the validation. In total, 16 ISCL datasets were intercompared—one for each ice shelf, for each year between 2018 and 2021. As example here, for each ice shelf, the validation results for January 2020 are provided, including ISCL comparison maps, distance profiles, histograms, and statistical summaries (see Figures 6.3–6.5 for Larsen-C, Figures 6.6–6.8 for Filchner, Figures 6.9–6.11 for Ronne 1, and Figures 6.12–6.14 for Ronne 2).

6.3.1 Larsen-C

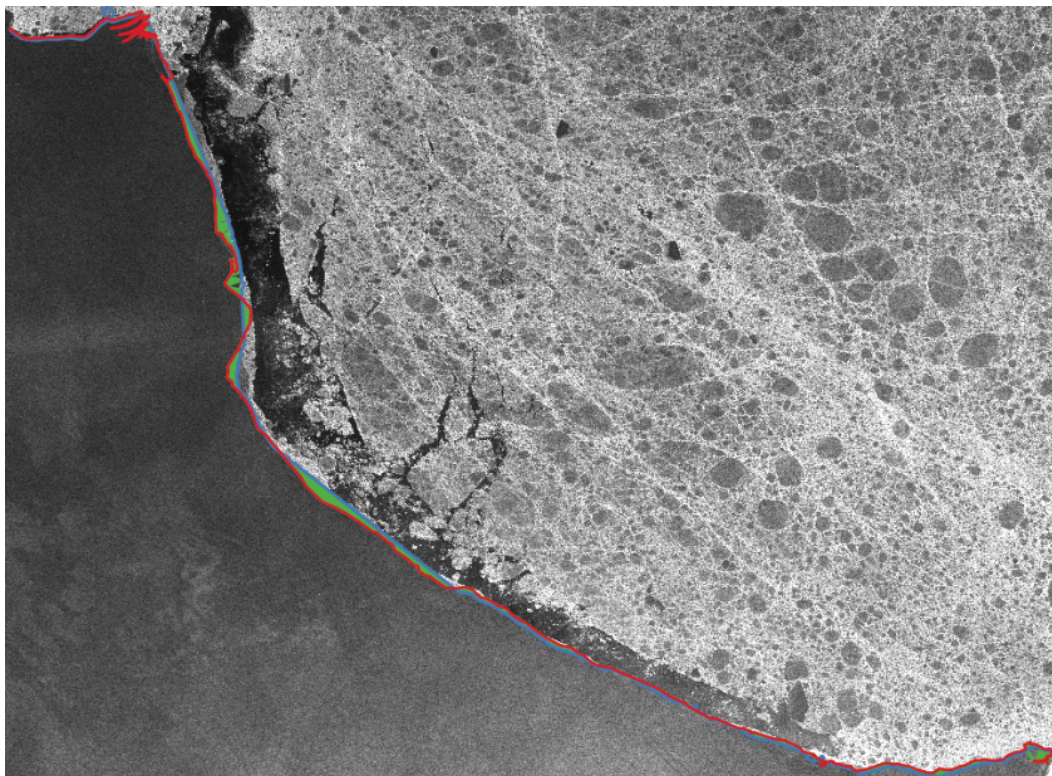


Figure 6.3: Comparison between the reference (red) and validation ISCL (blue) for January 2020, showing shortest distances computed every 100 m along the manually delineated calving front (green), on Larsen C.

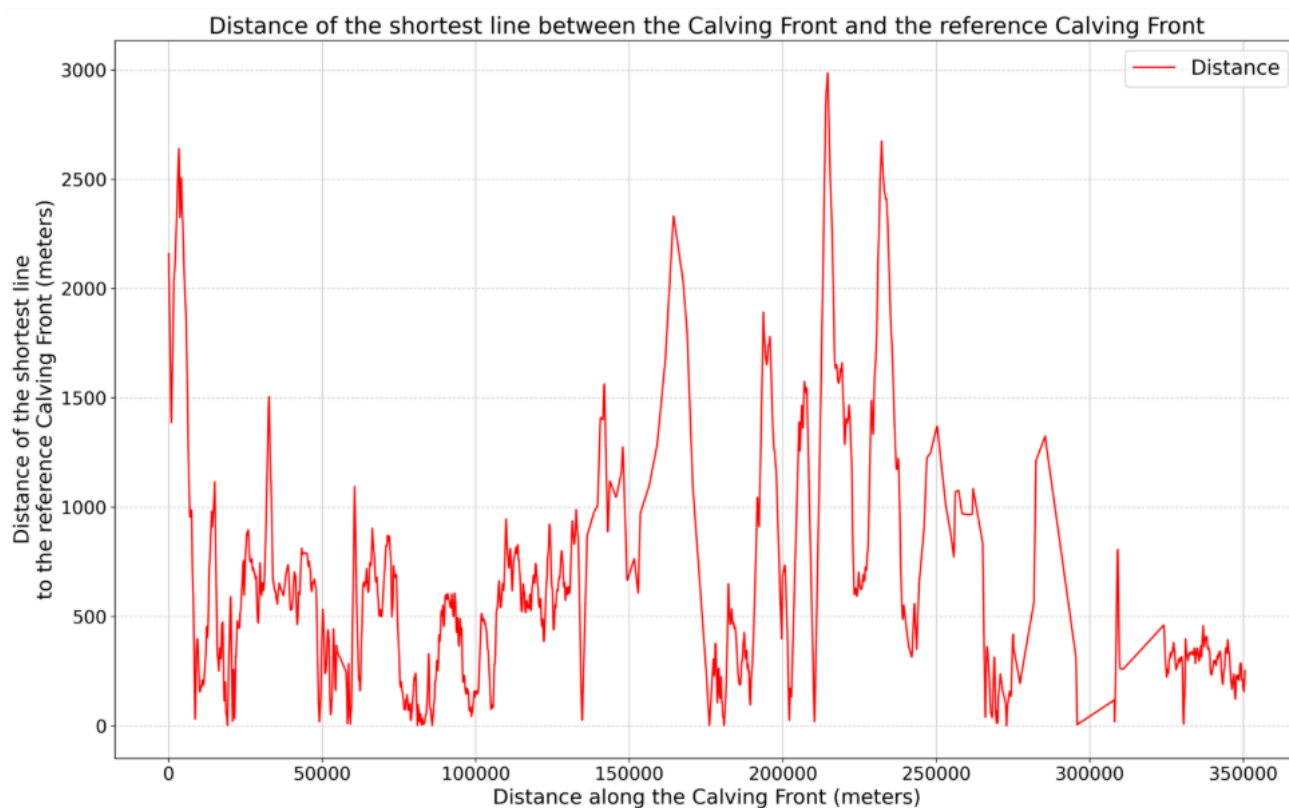


Figure 6.4: Profile of distances between reference and validation ISCL (Larsen-C, January 2020)

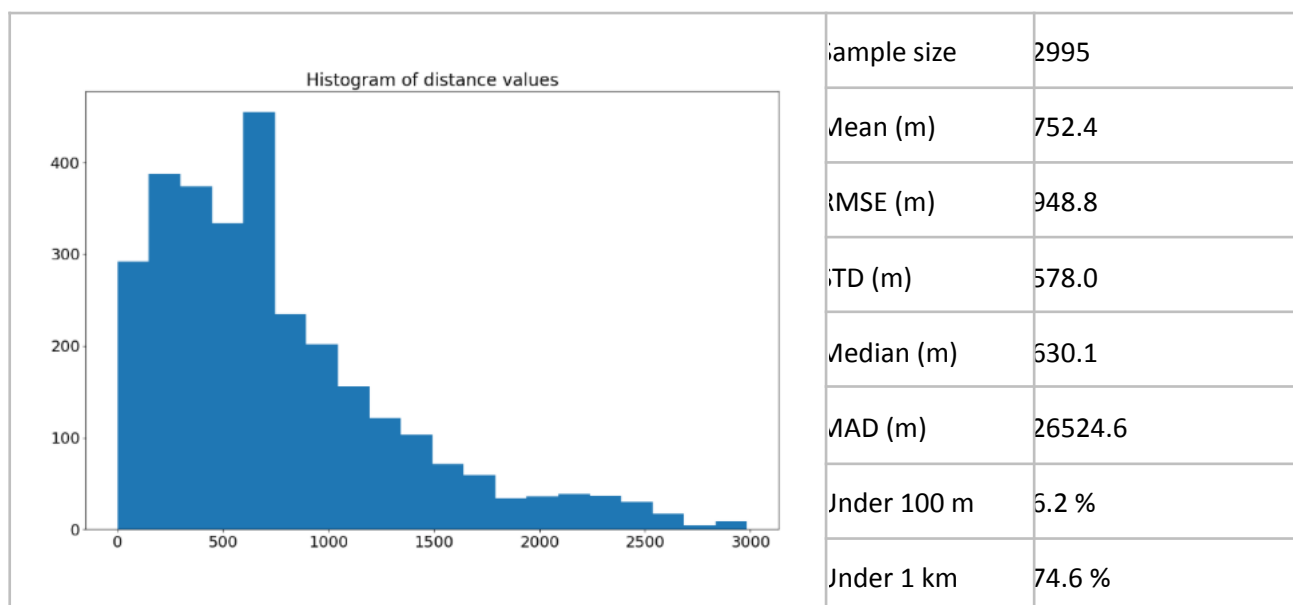


Figure 6.5: Histogram illustrating the distribution of distances (left) and summary statistics (right) comparing the reference and validation ISCL datasets for Larsen-C (January 2020).

6.3.2 Filchner

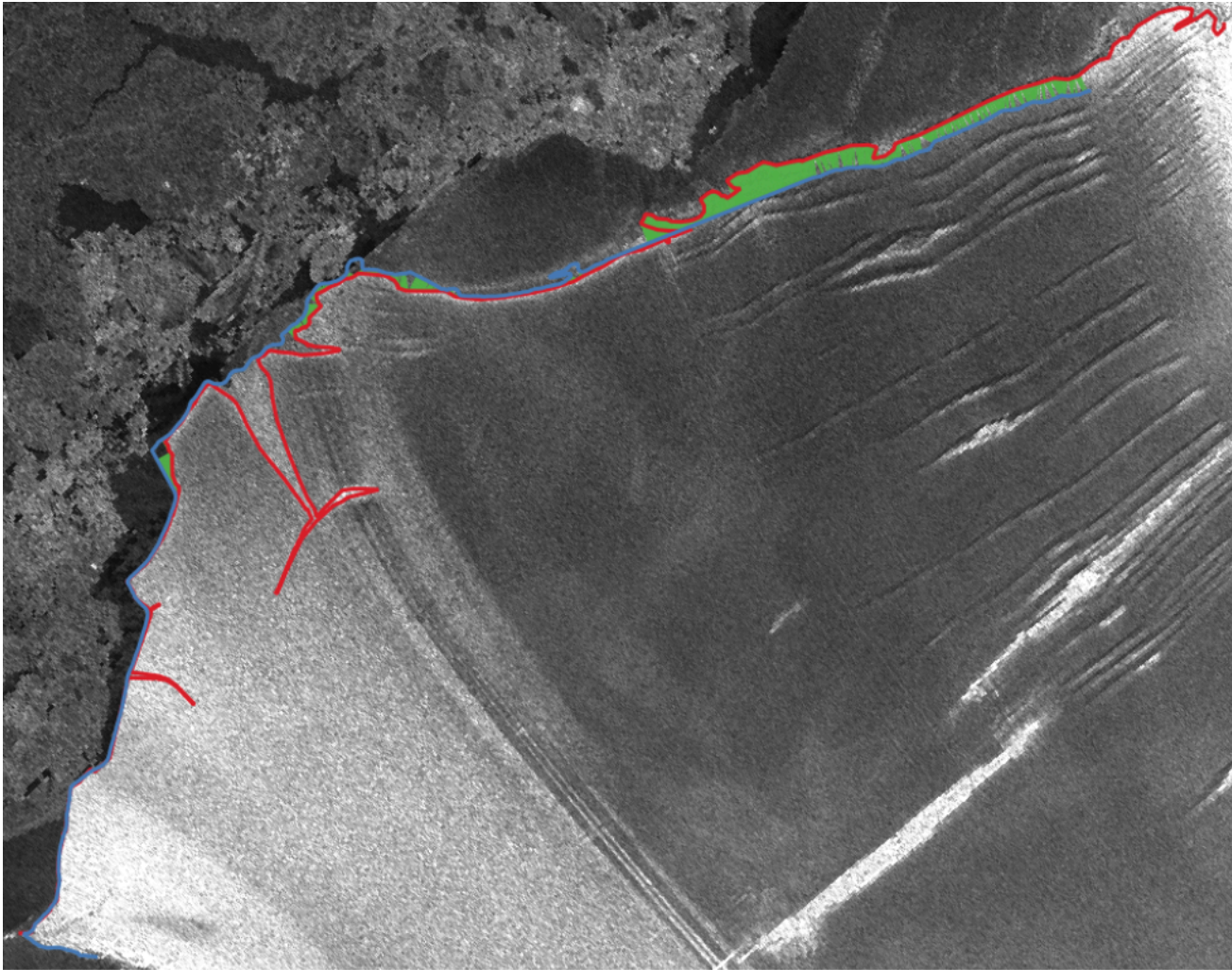


Figure 6.6: Comparison between the reference (red) and validation ISCL (blue) for January 2020, showing shortest distances computed every 100 m along the manually delineated calving front (green), on Filchner Ice Shelf.

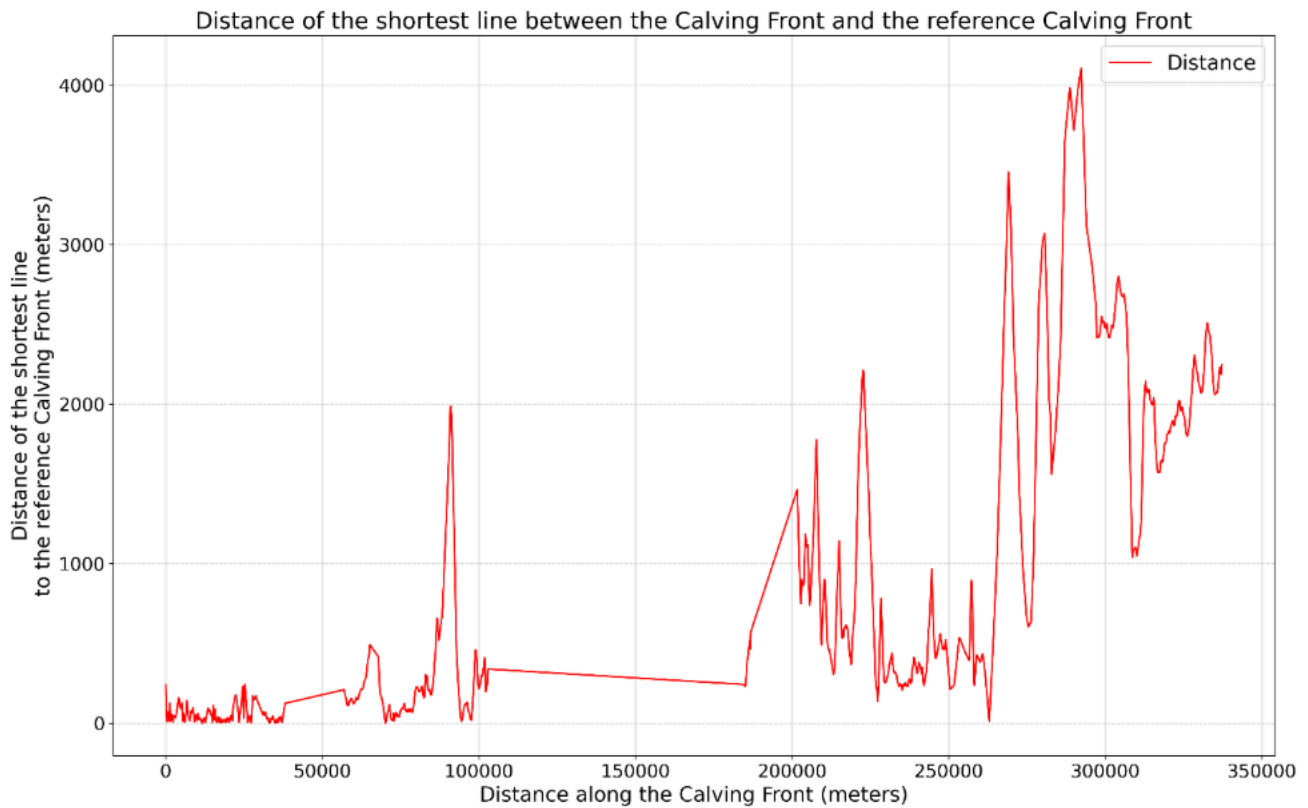
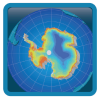


Figure 6.7: Profile of distances between reference and validation ISCL (Filchner, January 2020)

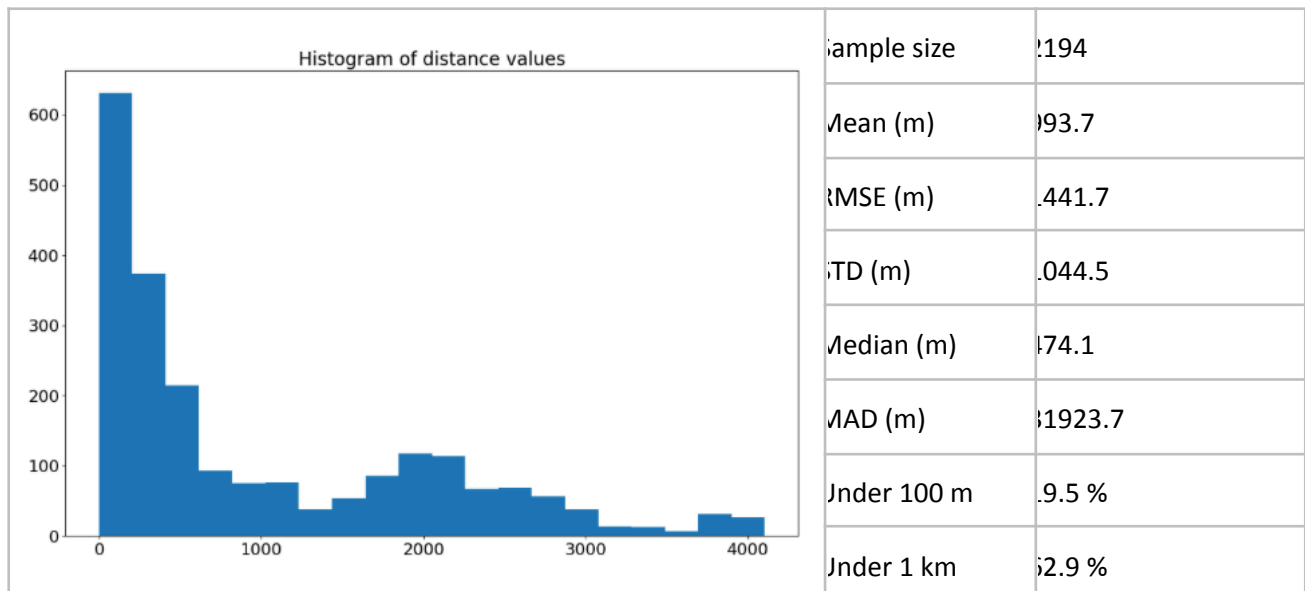


Figure 6.8: Histogram illustrating the distribution of distances (left) and summary statistics (right) comparing the reference and validation ISCL datasets for Filchner (January 2020)

6.3.3 Ronne 1

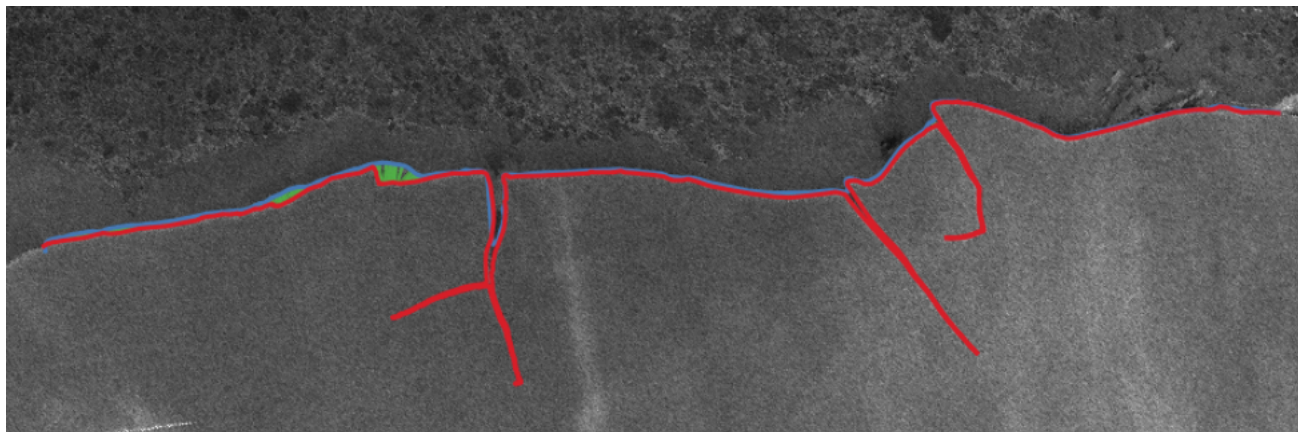


Figure 6.9: Comparison between the reference (red) and validation ISCL (blue) for January 2020, showing shortest distances computed every 100 m along the manually delineated calving front (green), on Ronne 1.

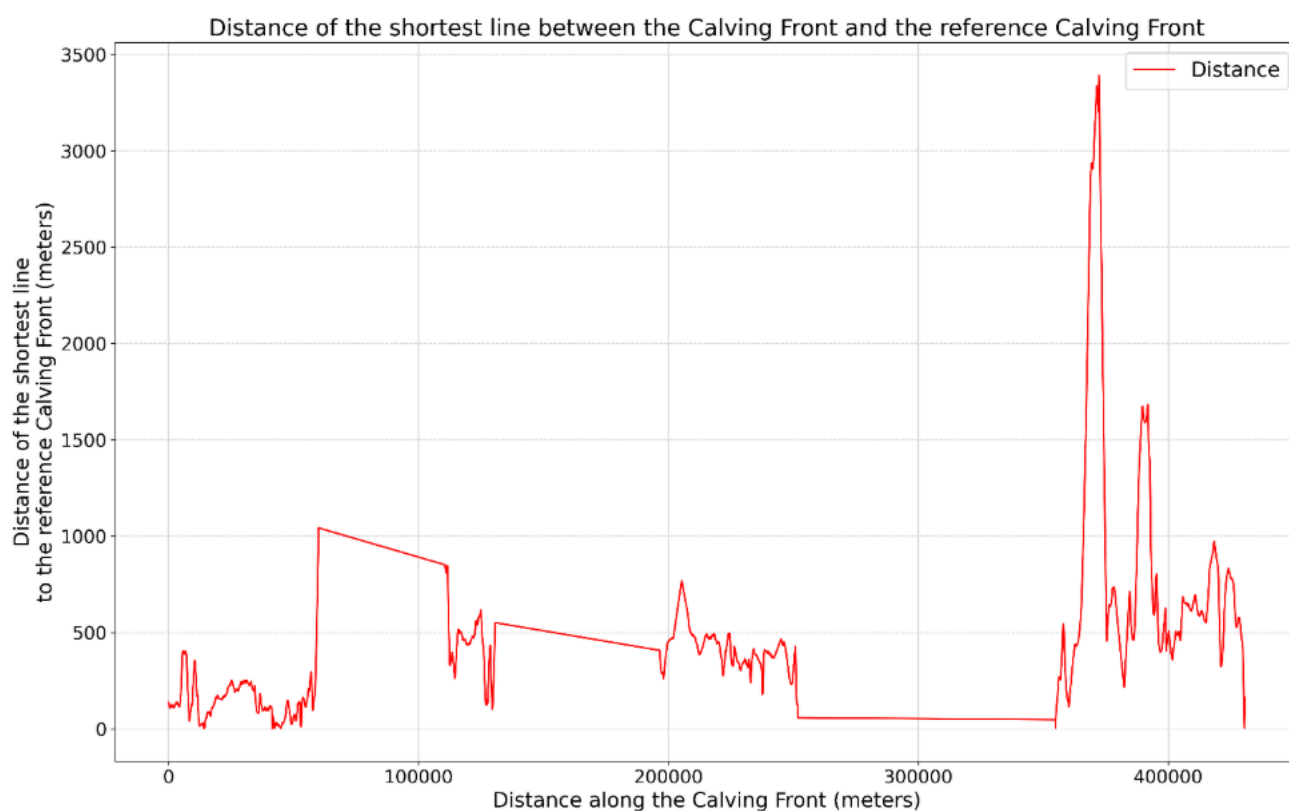


Figure 6.10: Profile of distances between reference and validation ISCL (Ronne 1, January 2020)

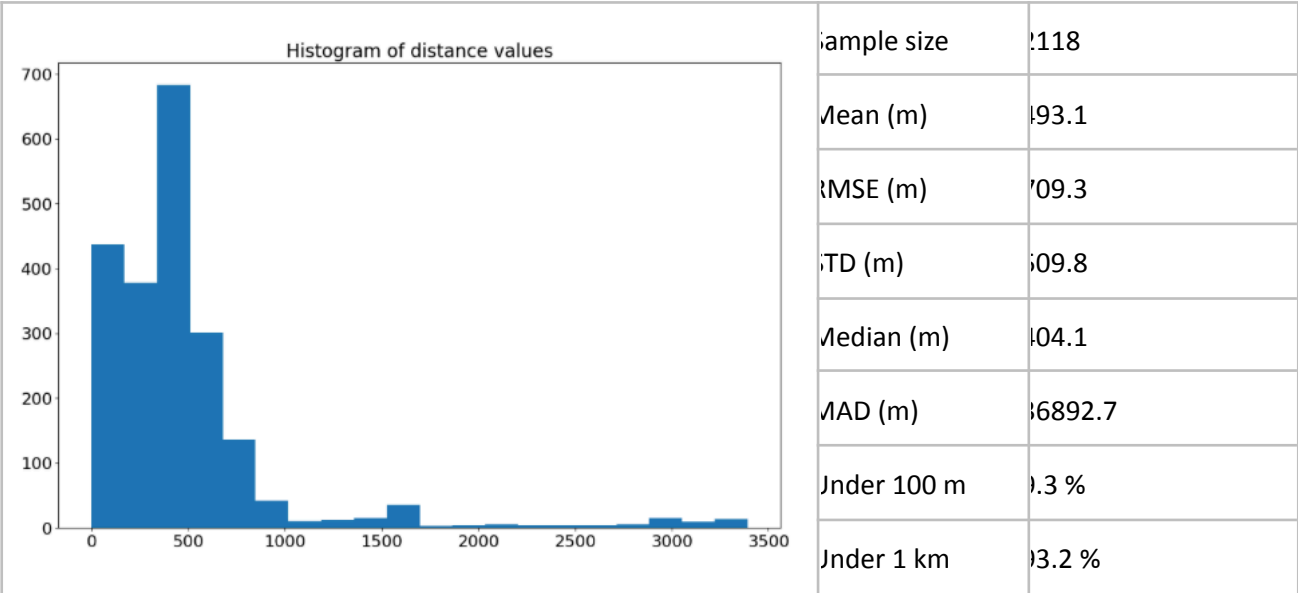


Figure 6.11: Histogram illustrating the distribution of distances (left) and summary statistics (right) comparing the reference and validation ISCL datasets for Ronne 1 (January 2020).

6.3.4 Ronne 2

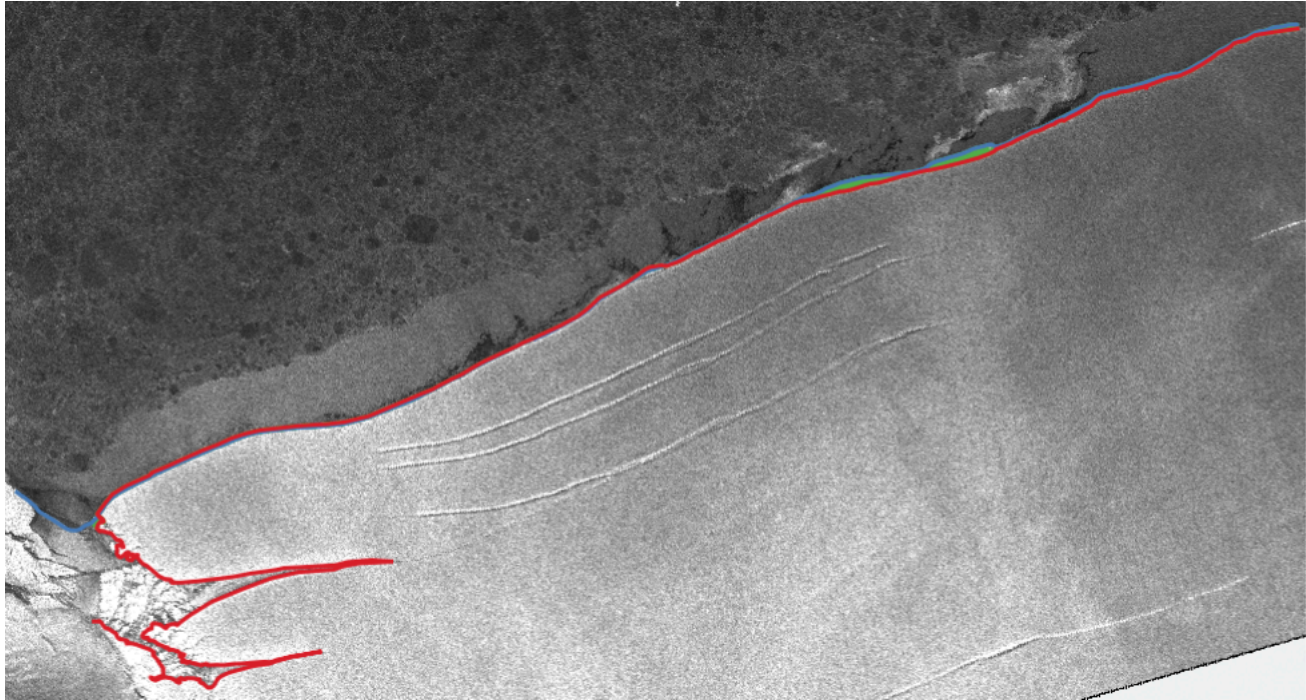


Figure 6.12: Comparison between the reference (red) and validation ISCL (blue) for January 2020, showing shortest distances computed every 100 m along the manually delineated calving front (green), on Ronne 2.

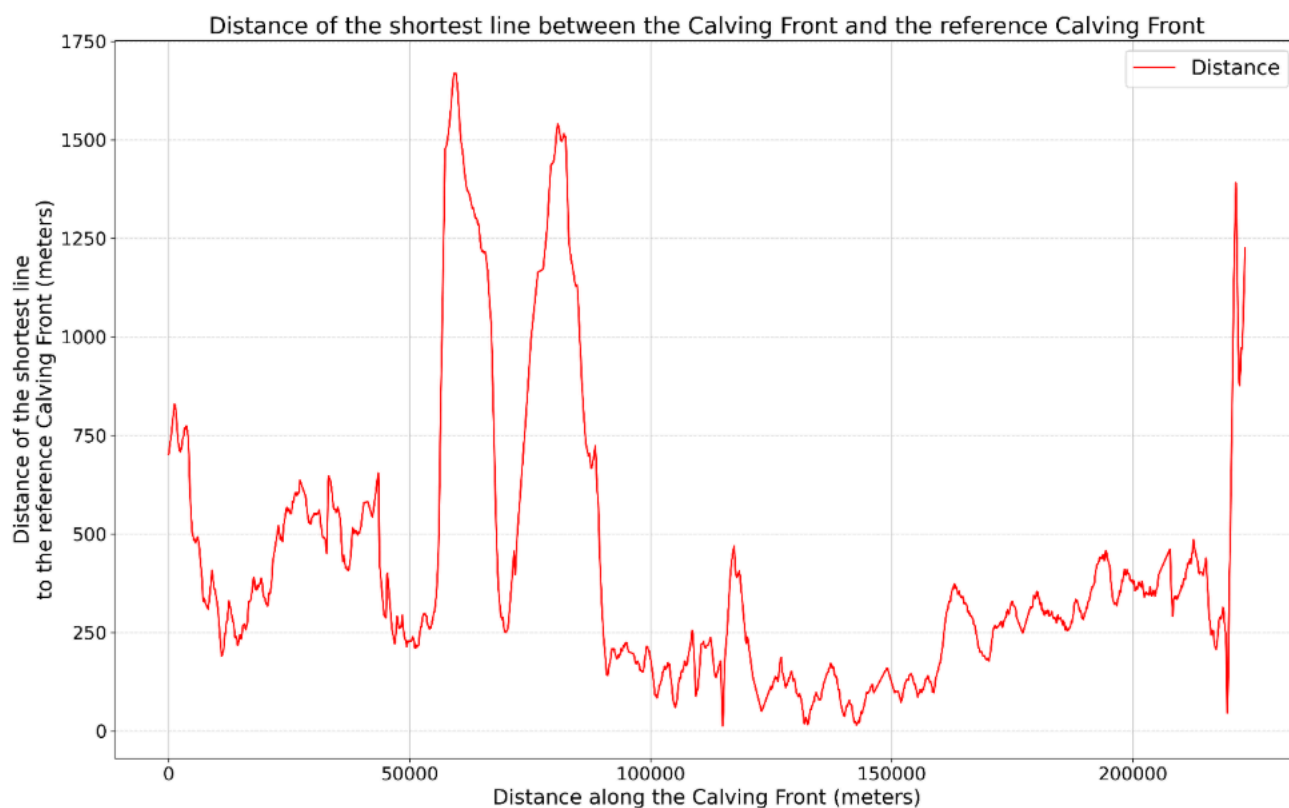


Figure 6.13: Profile of distances between reference and validation ISCL (Ronne 2, January 2020)

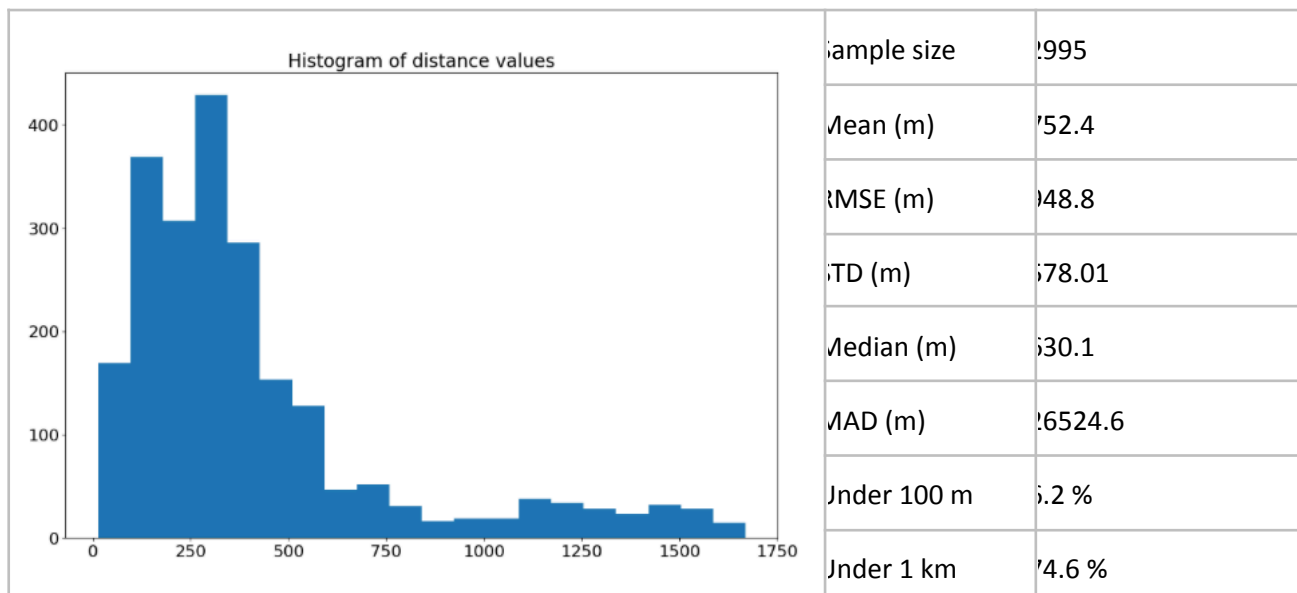


Figure 6.14: Histogram illustrating the distribution of distances (left) and summary statistics (right) comparing the reference and validation ISCL datasets for Ronne 2 (January 2020).

6.4 Overview and summary

Figure 6.15 and Table 6.2 summarize the validation results for each ice shelf, covering every January from 2018 to 2021. As illustrated in the previous figures, the coastlines of the ice shelves are generally smooth and not too complex. It is important to note that some more complex coastline features were excluded from this validation statistics, as their inclusion would have significantly altered the results.

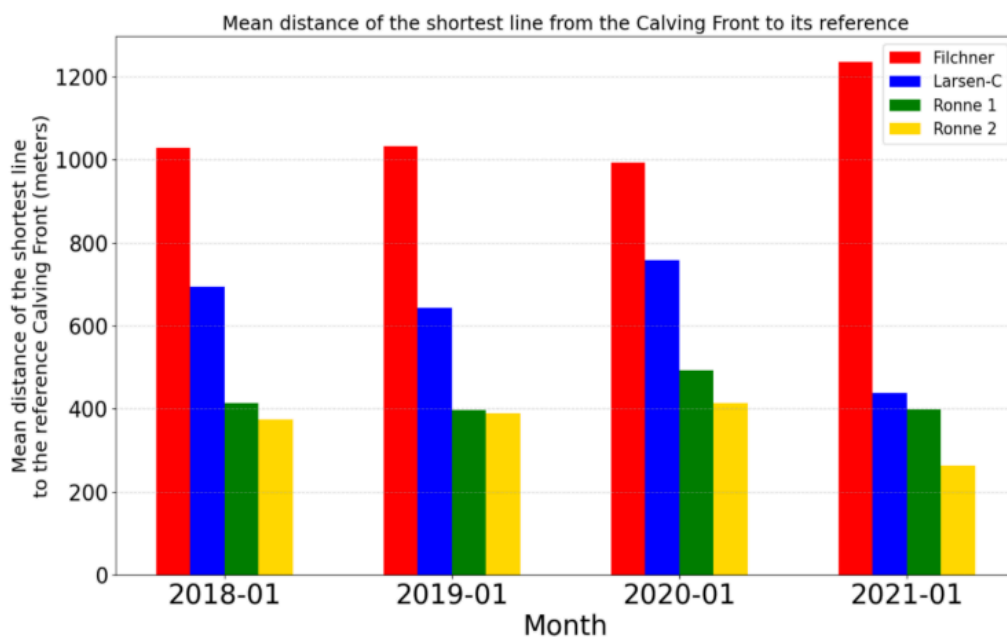


Figure 6.15: Graph showing the yearly mean distance between the manually delineated and ISCL coastlines for each ice shelf.

Ice Shelf	Date	Sample size	Mean (m)	RMSE (m)	STD (m)	Median (m)	MAD (m)	<100 m (%)	<1 km (%)
FILCHNER	2018-01-15	2182	1028.2	1593.0	1216.8	277.8	24494.0	18.1	64.0
FILCHNER	2019-01-01	2186	1032.3	1356.9	880.7	646.0	30709.8	4.3	71.1
FILCHNER	2020-01-17	2194	993.8	1441.8	1044.5	474.2	31923.7	19.5	62.8
FILCHNER	2021-01-18	2227	1235.9	1852.6	1380.1	607.9	33240.1	15.8	58.2
LARSEN-C	2018-01-18	2064	693.5	801.1	401.0	715.5	22044.2	6.1	79.6
LARSEN-C	2019-01-13	3211	644.3	750.6	385.1	612.9	27854.5	6.4	81.3

LARSEN-C	2020-01-08	2995	752.4	948.8	578.0	630.2	26524.6	6.2	74.6
LARSEN-C	2021-01-19	2870	438.9	689.8	532.9	224.6	27059.2	27.3	88.3
RONNE 1	2018-01-11	2052	414.9	609.8	446.9	280.7	33053.3	26.0	88.7
RONNE 1	2019-01-18	2013	396.9	539.7	365.7	271.7	33261.1	9.5	92.0
RONNE 1	2020-01-14	2118	493.1	709.3	509.8	404.1	36892.7	9.3	93.2
RONNE 1	2021-01-07	2124	399.6	850.3	750.5	152.6	38717.4	34.1	92.0
RONNE 2	2018-01-11	2380	373.6	434.5	221.7	384.0	20897.4	13.7	97.6
RONNE 2	2019-01-18	2445	389.6	412.0	133.9	407.3	18520.6	2.2	99.8
RONNE 2	2020-01-14	2223	413.5	543.9	353.3	312.0	16245.6	8.6	90.1
RONNE 2	2021-01-07	2486	263.4	347.7	226.9	224.8	22229.0	24.5	96.9

Table 6.2: Statistics of quality assessment

For the Larsen-C and Ronne ice shelves, more than 75% of the measured distances consistently fall below 1 km. This indicates a reasonable level of agreement with the reference calving front. However, only a small fraction (5–25%) of the distances are below 100 m. Together with the median values, this suggests that most discrepancies fall within a range of a few hundred meters.

The Filchner Ice Shelf shows similar results, though with a lower proportion of distances under 1 km. This difference is primarily attributed to an erroneous coastline detection in the eastern section of the ice shelf (see Figure 6.6). The high density of crevasses near and parallel to the coast possibly misled the algorithm, resulting in an incorrect identification of the true calving front. These errors broaden the distance distribution (reflected in higher RMSE, STD, and MAD values) and consequently increase the uncertainty regarding the product's overall accuracy.

In summary, the machine learning algorithm used to generate the ISCL performs effectively along smooth, straight ice shelf coastlines but struggles to accurately map areas with more complex geometries, such as those containing ice rifts.

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6.5 Recommendations for product improvement

The validation process exposed key areas where the current ISCL products could be improved:

1. Rift detection:
 - The detection of ice rifts within the ISCL is almost entirely absent, regardless of their length or width. In all rift zones, the ISCL appears to connect both sides without identifying the presence of rifts (Figures 6.16 and 6.17). This limitation may be due to the presence of fast ice or sea ice within the rift walls, which the machine learning algorithm fails to distinguish. The inability to detect such features is a major drawback, as ice rifts are critical for forecasting calving events. The use of elevation data in these regions might improve this.
2. Incomplete coverage:
 - Some ISCL products do not cover the full extent of certain ice shelves, introducing uncertainty in the affected regions (Figure 6.18). In particular the sides are often not covered.
3. Artefacts:
 - Visual artefacts were identified in some products that should be filtered out. An example can be seen in the Filchner Ice Shelf product from January 2021 (Figure 6.19).

6.6 Projection consistency

It is recommended that future products be provided in the Antarctic Polar Stereographic projection (EPSG:3031), to ensure consistency with other CCI datasets.

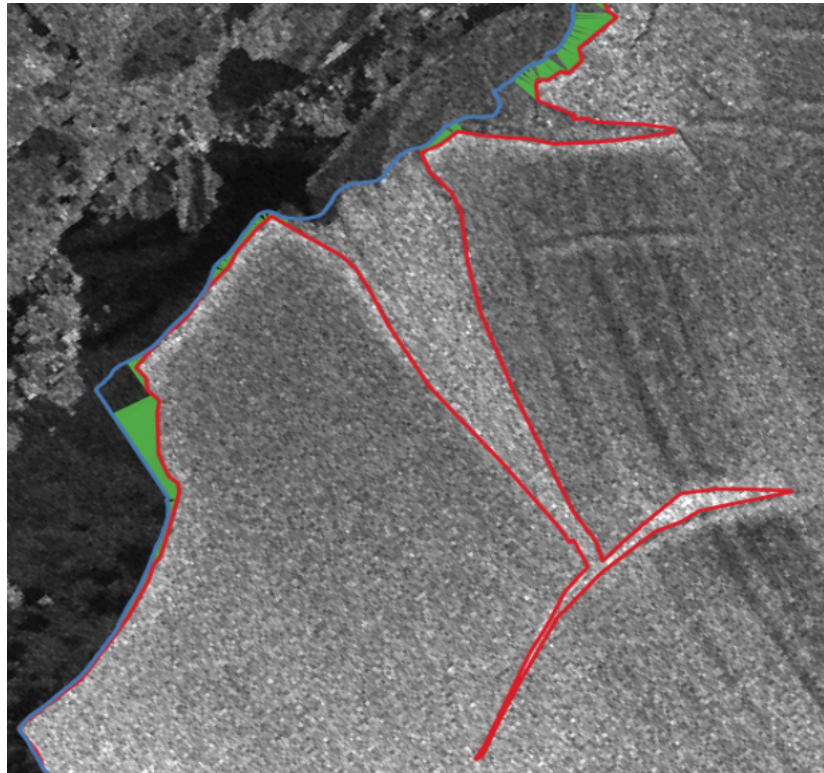
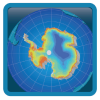


Figure 6.16: Comparison between reference (red) and validation ISCL (blue) in a rift zone (Filchner, January 2020)

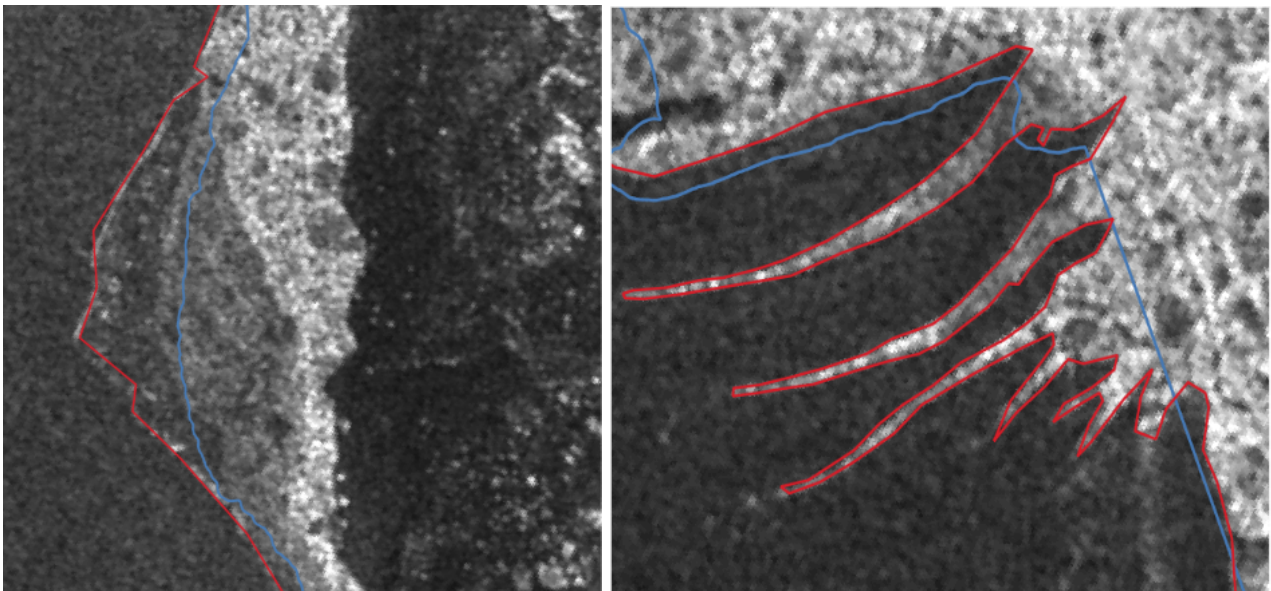


Figure 6.17: Comparisons between reference (red) and validation ISCL (blue) (Larsen-C, January 2020)

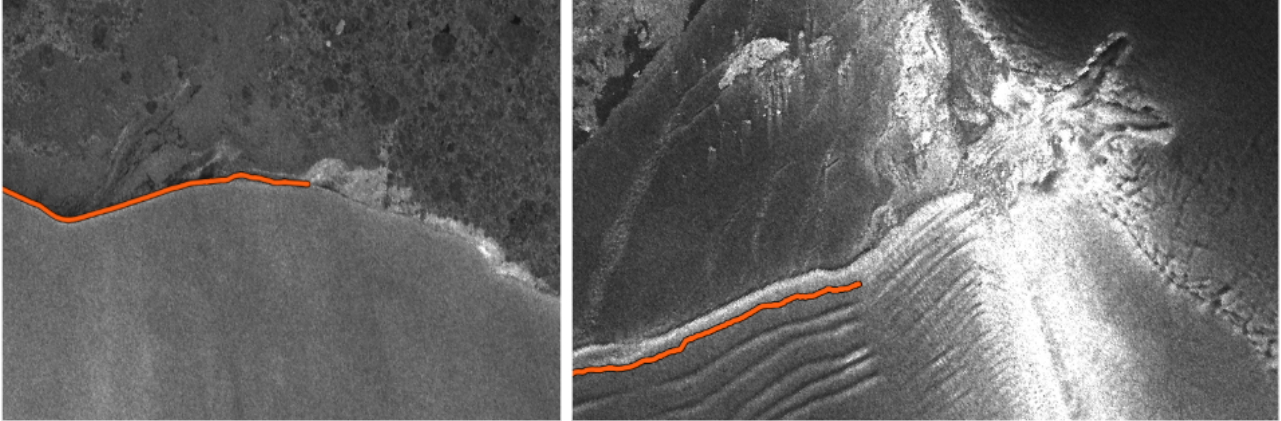


Figure 6.18: ISCL product of East Ronne (left) and East Filchner (right) Ice Shelves, January 2021

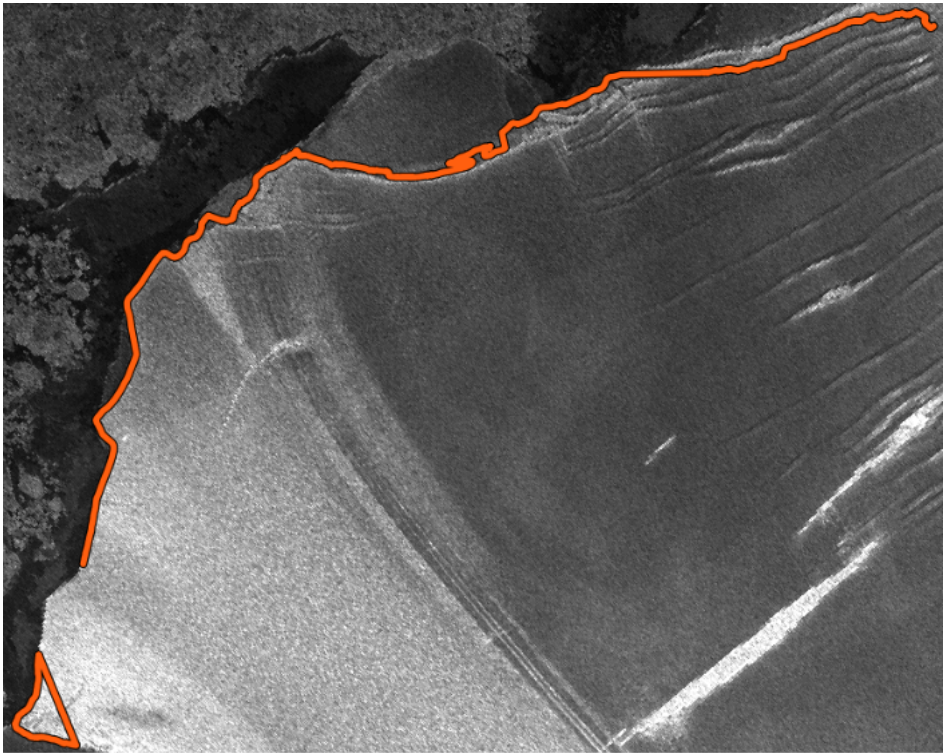


Figure 6.19: ISCL product of Filchner Ice Shelf showing artefact (January 2021)

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7 Uplift/Vertical ice velocity product

7.1 Validation data

Validation of the uplift product is difficult due to the dynamic nature of the observed uplift events, some of which propagate several kilometers between two Sentinel-1 acquisitions separated by 12 days (see Figure 7.1). Also, the small spatial scale (both horizontal extent (up to a few kilometers) and the very high InSAR sensitivity to uplift rates (on the order of mm/day to cm/day) means that few individual validation data sets are available. We use the ICESat-2 ATL11 Slope-Corrected Land Ice Height Time Series product (Smith,2023), generated with data from the ATLAS laser altimeter instrument on ICESat-2. This instrument generates line-profiles along ground tracks repeated at 91-day intervals. Compared to Sentinel-1, the coverage is sparse, both spatially and temporally, and it is generally infeasible to observe the fast-propagating drainage events, but the draining subglacial lake-like features that show sustained draining and filling over longer timescales before and after the drainage event (like the blue blob at the bottom of the Figure 7.1 plots) can sometimes be observed and used for a qualitative evaluation of the uplift product.

We examined the uplift product timeseries (that runs from 2017-08-30 to 2025-09-14 in 12-day steps) to identify areas exhibiting prolonged uplift or subsidence events covered by an ICESat-2 track, and within the timeframe of ICESat-2 (2019 and onwards). These points are illustrated in Figure 7.2.

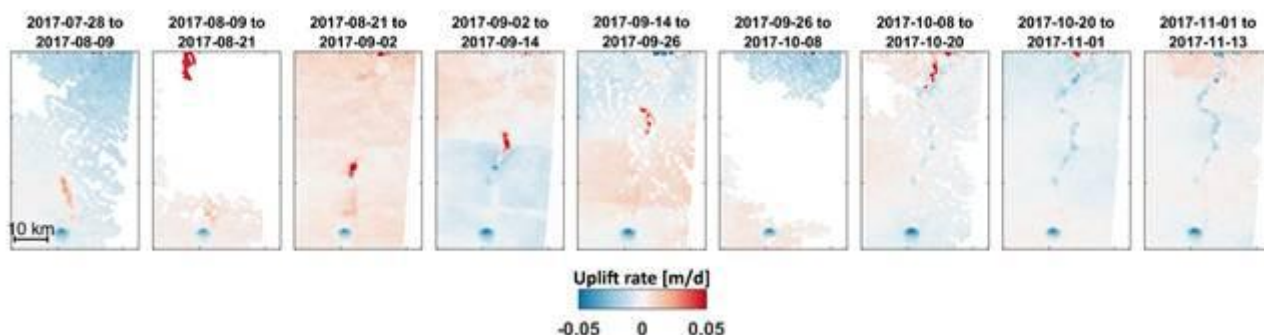


Figure 7.1: Example uplift rate maps from different timestamps from the product, showing a persistent subsidence signal at the bottom, and an uplift signal propagating towards the top of the image, leaving a trail of subsidence. This is interpreted as a subglacial lake draining, with the water traveling towards the coast.

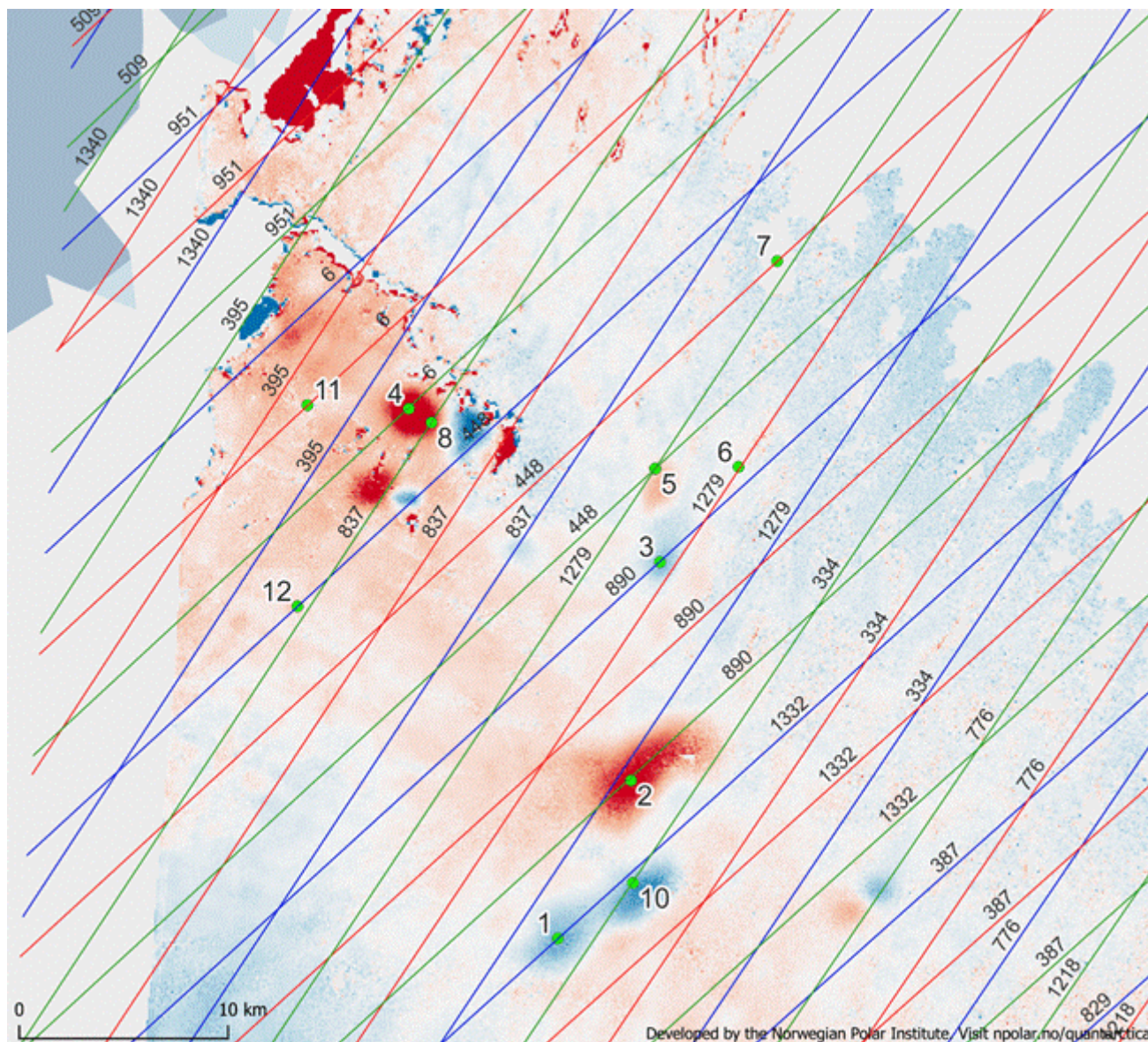


Figure 7.2: Location of points 1-12 used for validating the uplift product, plotted on top of a time snapshot (2019-06-30) of the product. The blue, red and green lines indicate reference ground tracks for the ICESat-2 beams, with track numbers. Note that point 9 coincides point 5 and is not shown. The reason for this is that points 5 and 9 sit at the crossover between ICESat tracks 448 and 1279 and thus represent different validation data sets.

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7.2 Validation procedure

The uplift product measures uplift *rates* with 12-day intervals (when coherence permits), whereas the ATL11 product measures absolute surface heights at 91-day intervals (when cloud cover permits). To compare the two at a given point, we must extract the uplift rate timeseries at that point and integrate it to obtain a cumulative uplift timeseries for each point. Then, ICESat-2 height timeseries are extracted for the point. As the cumulative uplift is very sensitive to both small systematic biases on the uplift rate and random walk integration noise, we interpolate the cumulative uplift at the ICESat-2 timestamps and calculate a linear fit to the difference between ICESat-2 heights and cumulative uplift at these points. The linear fit is then evaluated at and subtracted from all the cumulative uplift points before plotting and evaluating.

7.3 Validation outcome

The timeseries extracted using the approach described in the previous section are plotted on Figure 7.3, with the cumulative uplift in blue, and the ICESat-2 heights in red, referred to the left-hand y-axis. Additionally, the original uplift rates from the product are plotted as purple points, referred to the right-hand y-axis. The Pearson correlation coefficient, R , between the ICESat-2 and InSAR cumulative uplift measurements is indicated in the title of each subplot.

We see that the ICESat-2 heights show point-to-point fluctuations on the order of ± 0.2 m, whereas the cumulative uplift measurements seem significantly smoother. This is probably due to snowfall, as ICESat-2 measures the surface of the snow, but the C-band radar signal can penetrate several meters into the snow, thus being less sensitive to snowfall and measuring elevation closer to the ice surface. Even if the radar was sensitive to snowfall, elevation increases or decreases of the entire scene (caused by, e.g., widespread snowfall events and accumulation) would not be seen with InSAR, as InSAR measurements are always relative to some reference point in the scene.

When the uplift/subsidence is sustained for an extended period, such that the cumulative signal exceeds the ICESat-2 fluctuations (points 2,4, and 11), the correlation is high, with a value of 0.99 observed for the point with the largest variation of 4 m (point 2) over the period. This shows that uplift rates are correctly estimated by the product.

Where the total ICESat-2 height variation is within ± 0.2 m, the comparison shows only low to moderate levels of correlation. This shows that we cannot use ICESat-2 to validate the small, rapidly appearing and disappearing uplift events that typically show uplift rates on the order of 0.1 cm/d over a period of weeks to months. Over 91 days between two ICESat-2 acquisitions, such an uplift rate sums up to less than 0.1 m, less than the typical ICESat-2 fluctuations described above. However, the small-scale events show spatial patterns that are very similar to the sustained uplift events, leading us to conclude that the small, dynamic signals in the uplift rate product are indeed due to real uplift/subsidence. A complete validation of this would require observations from GPS receivers on the ice, which is not feasible.

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