ESA Climate Change Initiative
Antarctica Ice Sheet CCI+

Option 3 - Timeseries of ice discharge and IOM mass balance for the East and West Antarctic Ice Sheets from Sentinel-1

Product Validation Plan (PVP)

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Change Log

Issue	Author	Affected Section	Change	Status
1.0	Louise Sandberg Sørensen	All	First Version	Delivered to ESA

Acronyms and Abbreviations

Acronyms	Explanation
AIS	Antarctic Ice Sheet
ALOS-1/2	Advanced Land Observing Satellite-1/2
API	Antarctic Peninsula
BAS	British Antarctic Survey
CCI	Climate Change Initiative
CCN	Contract Change Notice
CSA	Canadian Space Agency
DInSAR	Differential SAR Interferometry
DLR	Deutsche Zentrum für Luft- und Raumfahrt
ENVEO	Environmental Earth Observation
ENVISAT	Environmental Satellite
ERS-1/2	European Remote Sensing satellite 1 & 2
ESA	European Space Agency
GPS	Global Positioning System
InSAR	Interferometric synthetic-aperture radar
IV	Ice Velocity
MEaSUREs	Making Earth System Data Records for Use in Research Environments
MFID	Mass Flux Ice Discharge
NASA	National Aeronautics and Space Administration
NSIDC	National Snow and Ice Data Center
OLI	Operational Land Imager
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PGC	Prince Gustav Channel
PVIR	Product Validation and Intercomparison Report
PVP	Product Validation Plan
QA	Quality Assessment
RMSE	Root-Mean-Square Error
RR	Round Robin
SAR	Synthetic Aperture Radar
TDX	TanDEM-X
TSX	TerraSAR-X
UL	University of Leeds
USGS	United States Geological Survey
WP	Work Package

1 Introduction

1.1 Purpose and Scope

This document contains the Product Validation Plan (PVP, O3-D1.1) for CCN Option-3 as part of the Antarctic Ice Sheet CCI+ project Phase 2, in accordance with the contract and proposal [AD1 and AD2]. The PVP is delivered as part of WP3100 - Requirements Baseline - and describes data and methods/procedures for quality assessment and validation of the main products to be generated in the project: ice velocity (IV), mass flux ice discharge (MFID) and mass balance (MB). The results of the validation will be reported in the Product Validation and Intercomparison Report (PVIR, O3-D4.1) in WP3400. The PVP contains the procedures for quality assessment of geophysical products, intercomparison strategies with independent estimates, consistency check methodologies, and information on available validation and intercomparison datasets.

The performance of the satellite-based ice velocity (IV) product will be assessed by comparing it with available in-situ GPS data where possible. In regions where GPS data is not available, we will use gridded maps and stable terrain areas to perform the validation. Additionally, we will compare the IV product with other publicly available ice velocity datasets to further assess its accuracy and consistency.
For validating the Mass Flux Ice Discharge (MFID), we will compare our ice discharge estimates for major outlet glaciers with values reported in the literature. The differences between our estimates and the published data will be analyzed to understand the causes of any discrepancies. This process will include a detailed examination of uncertainties related to BedMachine ice thicknesses, which may affect the discharge estimates.

To validate the Mass Balance (MB), we will compare our basin-scale solid ice discharge estimates with GMB mass change estimates from the GRACE missions. Within the AIS CCI+ approximately monthly estimates of GMB mass changes from the GRACE missions are produced. These monthly GMB mass changes are the difference between surface mass balance and discharge within that basin. We will compare basin scale solid ice discharge estimates with GMB time series and SMB from available Regional Climate Models and investigate how well they agree.

1.2 Document Structure

This document is structured as follows:

- Chapter 1 contains an introduction to the document
- Chapter 2 describes validation strategies and validation resources for IV,
- Chapter 3 describes validation strategies and validation resources for MFID,
- Chapter 4 describes validation strategies and validation resources for MB,
- Chapter 5 lists the references

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	1.0
AD2	ENVEO-NU-DTU-SNT-AISCCI+-P2-Option3-MFID-001_v06	Technical proposal for Option 3	01.12.2023	

Table 1.2: List of Reference Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
RD1				
RD2				

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

2 Validation and intercomparison Datasets

2.1 In-situ GPS

Time series of GPS data from GPS receivers located on the ice sheet are very suited for validation purposes. The availability of such data is unfortunately very limited. We will search through data sites and literature to find relevant data (if any) for ice velocity validation in this project.

2.2 Ice Velocities from other sources

For ice velocity intercomparison, we will utilize datasets provided by the *Inter-mission Time Series of Land Ice Velocity and Elevation (ITS_LIVE)* program, part of NASA's MEaSUREs initiative. The ITS_LIVE portal, accessible at https://its-live.jpl.nasa.gov/, offers ice velocity data measured in meters per year [m/yr]. This data can be visualized as a time series at specific locations across the ice sheet, as illustrated in Figure 2.1.

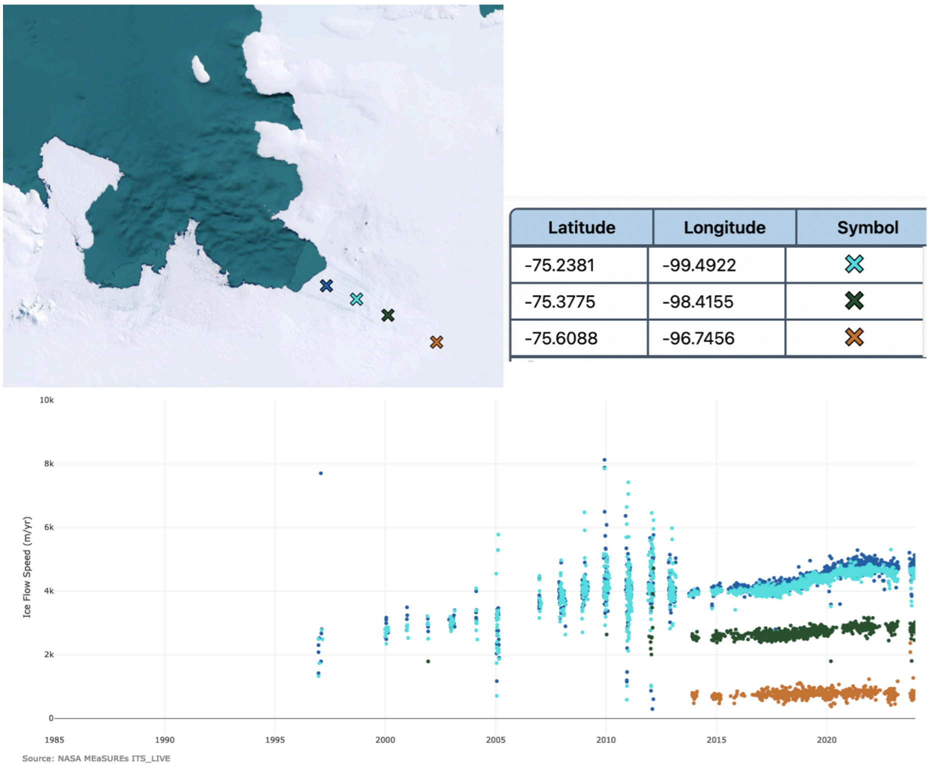

***Figure 2.1: Ice velocity time series from Pine Island Glacier from ITS_LIVE* NASA MEaSURE program.**

The chosen time series can easily be downloaded as a CSV file, where it is possible to see from which satellite the data comes from in the time series.

The ITS_LIVE dataset offers global spatial coverage, ensuring that all of the Antarctic Ice Sheet (AIS), is fully represented. The data are provided at a high spatial resolution of 120 meters, making it suitable for detailed analyses of ice dynamics and localized ice flow features.

The temporal coverage spans nearly four decades, from 1985 to the present, enabling long-term analyses of changes in ice flow behavior. However, the temporal resolution of the data varies depending on satellite availability and observation frequency. For some regions and time periods, ice velocity measurements are available monthly, whereas, for others, data may be at an annual frequency.

From approximately 2014 and onwards to 2022 a complete yearly composite of glacier velocities can be downloaded as both NetCDF file and a QGIS project file. The spatial coverage for 2014 can be seen in Figure 2.2.

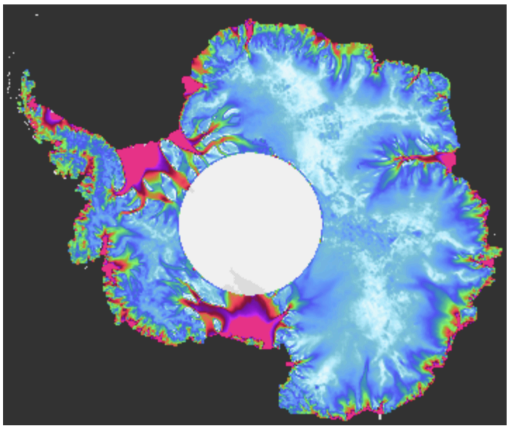

Figure 2.2: The spatial coverage of the yearly ice velocity composite from 2014 that can be downloaded from ITS_LIVE.

2.3 Gravitational Mass Balance

We will use basin scale mass change estimates for the Antarctic Ice Sheet derived from GRACE and GRACE-FO data. The GRACE satellites measure variations in Earth's gravity field, which can be interpreted as changes in mass on the Earth's surface. The data is available at a monthly scale for the period 2002-present, with an approximately one-year data gap between the two missions in 2017/2018. This product is part of the ESA Climate Change Initiative for Antarctic Ice Sheet data portfolio (available at *data1.geo.tu-dresden.de/ais_gmb*), and the methodology is described in detail in Groh & Horwath (2021). To derive this data product, the authors employ Tailored Sensitivity Kernels (TSKs), which are specially designed weight functions. TSKs minimize both GRACE/GRACE-FO mission errors (e.g., north-south striping patterns in the data) and signal leakage (errors caused by low spatial resolution leading to misattribution of signals). The kernels are optimized using a formal adjustment process that balances mission errors and mass signal assumptions across the AIS and surrounding regions.
The final mass-change products are provided in two formats:

1. Gridded mass change time series for a dense 50 km × 50 km grid over the AIS.
2. Basin-averaged mass change time series for defined drainage basins of the AIS.

The study uses synthetic data to validate the TSK approach and quantify potential leakage errors. By optimizing the sensitivity kernels, the authors ensure robust mass change estimates across AIS, its drainage basins, and specific ice shelves. This product accounts for uncertainties from signal leakage, GIA corrections, and data uncertainties.

Figure 2.3 shows the basin definitions and examples of the data product for selected drainage basins.

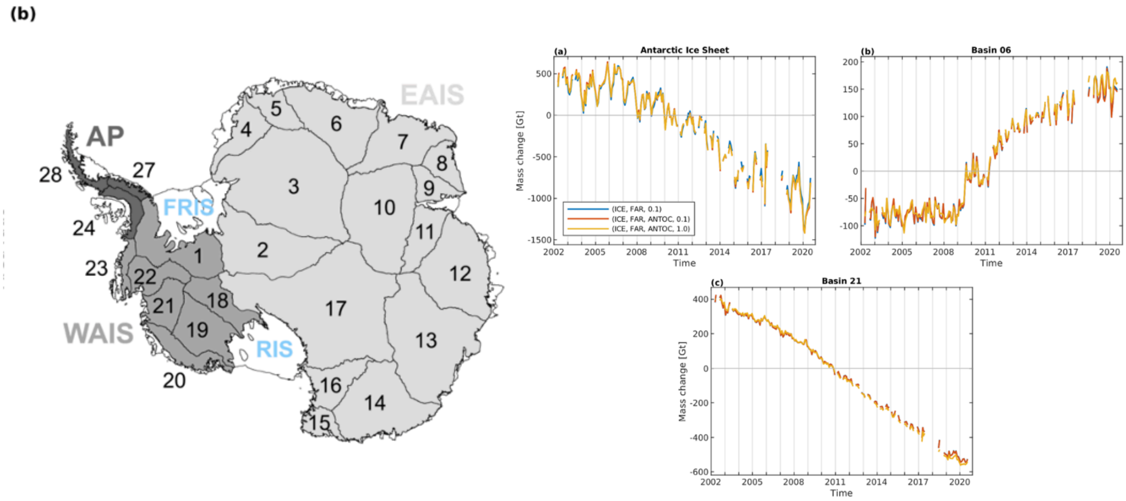

Figure 2.3: Examples of mass change time series for selected drainage basins in Antarctica. Basin outlines shown in the map. Adapted from Groh & Morwath (2021)

2.4 Surface Mass Balance

Surface Mass Balance (SMB) estimates for Antarctica are generated by Regional Climate Models (RCMs). Different models are available and e.g. Mottram et al., (2021) describe the output from a range of runs from: COSMO-CLM2, HIRHAM5, MAR3.10, MetUM, and RACMO2.3p2, all driven by ERA-Interim climate reanalysis data. Mottram et al (2021) find that the model ensemble mean SMB estimate is 2329 ± 94 Gt yr^{-1} for the 1987–2015 period, but that the SMB shows significant spatial variability, particularly in West Antarctica and regions with complex topography. They also conclude that models with advanced snow schemes (e.g., RACMO2.3p2) perform better in certain regions, reflecting the importance of including processes like refreezing and sublimation. Also, resolution and ice mask discrepancies may influence integrated SMB estimates.

The different models are described in Table 2.1, adapted from Mottram et al. (2021).

Model	Period	Resolution [km] (°)	Nudging	SMB scheme	Topography dataset	Atmospheric levels
COSMO-CLM^2	1987–2016	25 (0.22)	Yes	Yes	GLOBE[a]	40
HIRHAM5	1979–2017	50 (0.44); 12.5 (0.11)	No	No	GTOPO[b]	31
MetUM	1979–2018	50 (0.44)	Reinitialized	No	GLOBE[a]	70
$MAR_{v3.6}$	1979–2018	35	Yes	Yes	Bedmap2[c]	23
$MAR_{v3.10}$	1981–2018	35	Yes	Yes	Bedmap2[c]	24
$RACMO2.1P_{v1}$	1979–2012	50 (0.44)	No	Yes	RAMPv2[d]	40
RACMO2.3p2	1979–2018	27 (0.25)	Yes	Yes	Cook, Bamber[e]	40

Table 2.1: Summary of differences and similarities between the RCMs.

The different model outputs are shown in Fig 2.4, which shows integrated SMB and specific SMB (SSMB) for the models included in the as well as the ensemble mean and standard deviation shown.

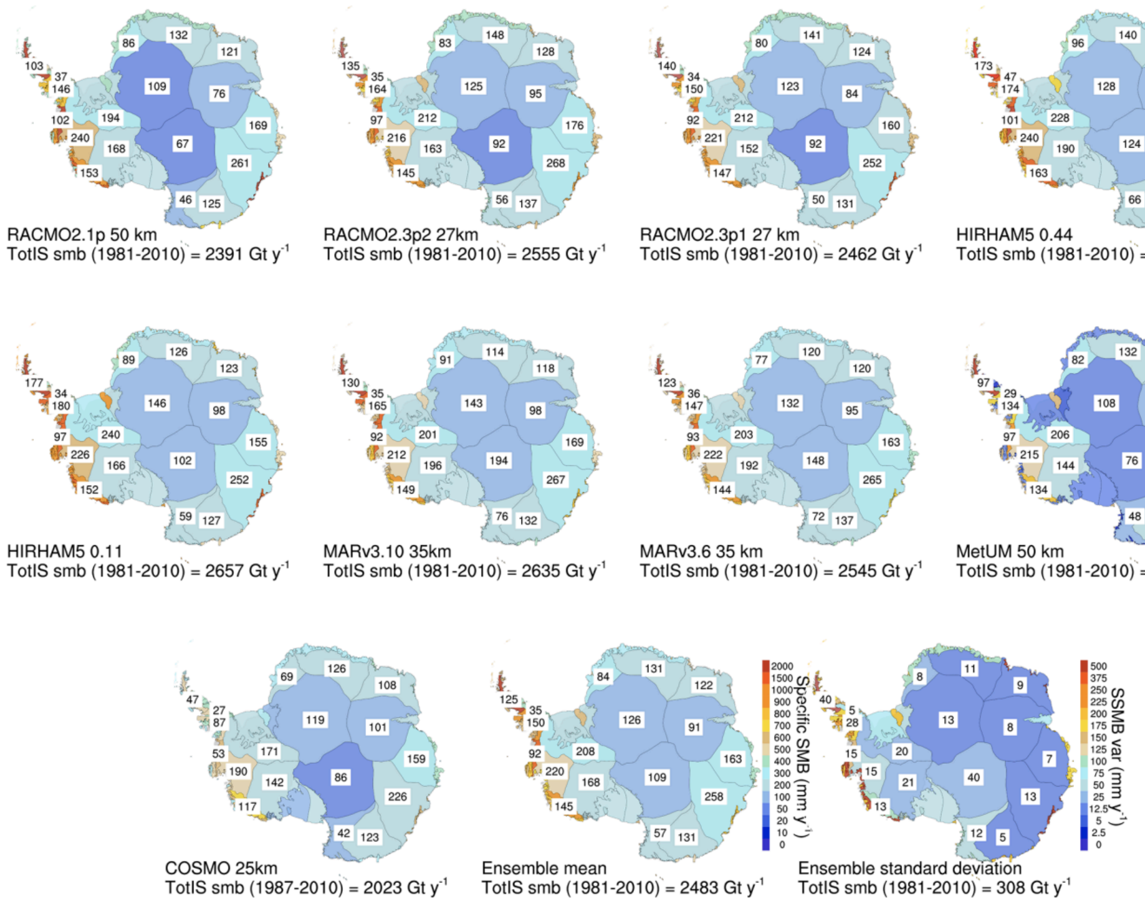

Fig. 2.4: Integrated SMB and specific SMB (SSMB) as well as the ensemble mean and standard deviation for the models included in Mottram et al., (2021).

Unfortunately, to our knowledge, these model runs are not available for download. We will search additional literature and data sites to see if any relevant output is available. If not, we will contact the institutes that run these models and ask for access to the models. We note though that this dataset is not an essential part of the proposed validation activities - but could serve as a supplement in the validation/intercomparison process.

2.5 Basal melt fluxes

Ideally, we would like to include basal melt flux estimates at basin scale in the proposed intercomparison activities, as this is a contribution to the total mass balance of the ice sheet. While such a product is available for Greenland (Karlsson et al., 2021), no such dataset is available for Antarctica (to our best knowledge).

Dawson et al (2022) investigated how changes in the basal thermal state of the Antarctic Ice Sheet may influence ice mass loss and contribute to sea-level rise. Using the Ice-sheet and Sea-level System Model (ISSM), the authors simulate century-scale impacts of idealized basal thawing in regions where the ice-bed interface is near the pressure melting point. Results show that even small increases in basal temperatures can trigger thawing, particularly in the George V-Adélie, Enderby, and Kemp Land regions of East Antarctica, which are currently sustained by frozen-bed patches. The study highlights the importance of basal thermal conditions, which remain poorly constrained due to limited observations.

3 Validation Procedures

3.1 Ice Velocities

The validation and intercomparison of the AIS_CCI+ ice velocity (IV) products will be conducted using ITS_LIVE data, which provides satellite-based ice velocity measurements and GPS data. This will involve 4 approaches:

- **Selected Glaciers**: The ice velocity from the AIS_CCI+ products will be compared to ice velocity measurements from specific glaciers that are part of the ITS_LIVE dataset. These glaciers are selected for their relevance to the study and represent a variety of ice flow regimes.

- **Antarctic-wide**: In addition to individual glaciers, the validation will also involve comparing the AIS_CCI+ IV products against the yearly ice velocity composite that covers the entire Antarctic ice sheet from the ITS_LIVE data from 2014 and onwards.

- **Stable ground areas**: An additional quality assurance (QA) check will be conducted by analyzing regions of stable ground (areas where ice velocity should be negligible, such as bedrock). In these regions, no ice movement is expected, so any detected velocity can be attributed to errors or biases in the IV products. This serves as an internal consistency check, helping to identify and quantify potential systematic biases in the data. For this, we will use a rock outline shapefile derived from LandSat-8 Operational Land Imager (OLI) from the study by Burton-Johnson et al. 2016, see Figure 3.1.

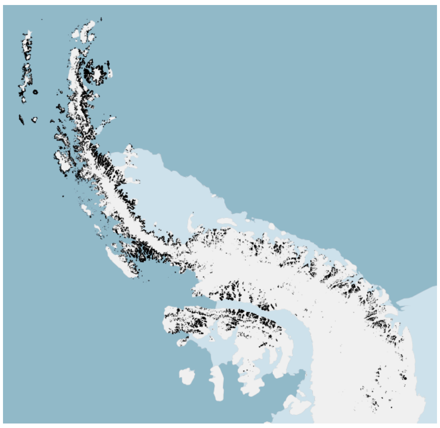

Figure 3.1: Map of the Antarctic Peninsula showing in light blue floating ice shelves and in black the Burton-Johnson rock outcrop shapefile used for the stable terrain test (Burton-Johnson et al., 2016).

- **Independent In-Situ GPS data**: The IV products will be validated with in-situ GPS data if/where available, though such data is very sparse, providing trusted ground-based validation for ice velocity measurements.

The validation metrics include the mean and RMSE of velocity differences for the horizontal components (easting and northing). For intercomparisons, reference datasets from a similar time span are used to avoid biases from glacier dynamics. Validation datasets will be resampled and/or collocated to match the grid spacing, projection, and extent, with comparisons limited to overlapping areas.

Test	Description	Metrics
#1	Intercomparison with in-situ GPS data (if available)	Mean, RMSE [m/d] East/North
#2	Statistics over stable terrain; mean should be 0 m/d	Mean, RMSE [m/d] East/North
#3	Intercomparison with available independent IV data products from e.g. ITS_LIVE	Mean, RMSE [m/d] East/North
#4	Local/regional assessment of IV quality based on variability and number of data available	number of data, STD

Table 3.1: Summary of validation activities and metrics for evaluation

3.2 Mass Flux Ice Discharge

The mass flux ice discharge is calculated using ice velocity (IV) and ice thickness along the flux gate. The validation focuses on the IV data (see previous section).

In addition, an intercomparison will be carried out with previously published studies that focus on selected outlet glaciers and basins, providing an additional means of validation. This includes benchmarking against results reported in the literature, such as those by Rignot et al. (2008), Wuite et al. (2015), Gardner et al. (2018), and Rignot et al. (2019). These studies provide a reference for evaluating the performance of the datasets produced in this project.

Validating the other primary input datasets, such as ice thickness and grounding lines, is beyond the scope of this project.

3.3 Input Output mass balance

To assess the results from the Input Output mass balance method applied here, we will compare it to the GMB dataset, which is described in Section 2.3.

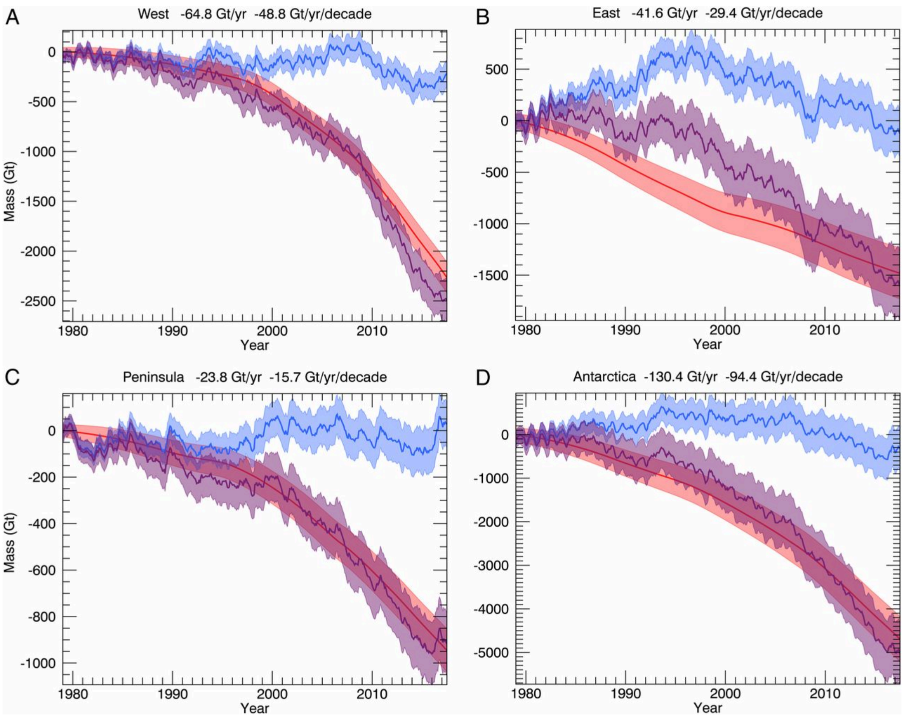

Figure 3.2: From Rignot et al 2019. Time series of cumulative anomalies in Surface Mass Balance (SMB, blue), ice discharge (D, red), and total mass (M, purple), shown with error bars in billions of tons, for the following regions: (A) West Antarctica, (B) East Antarctica, (C) Antarctic Peninsula, and (D) the entire Antarctic Ice Sheet. The figure includes the mean mass loss (in billions of tons per year) and the rate of acceleration (in billions of tons per year per decade) over the period 1979–2017.

Comparing different RCM outputs of SMB (see Sect. 2.4) was conducted in a study by Rignot et al. (2019). However, this comparison focused on the eastern and western segments rather than on the drainage basin scale (see Figure XX). Therefore, we will divide our basin-based data into eastern and western regions to facilitate comparison with the Rignot study, while also reviewing additional information from other articles.

4 References

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.

Dawson, E. J., Schroeder, D. M., Chu, W., Mantelli, E., & Seroussi, H. (2022). Ice mass loss sensitivity to the Antarctic ice sheet basal thermal state. *Nature Communications*, *13*(1), 4957.

Gardner, A. S., G. Moholdt, T. Scambos, M. Fahnestock, S. Ligtenberg, M. van den Broeke, and J. Nilsson, 2018: Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years, Cryosphere, 12(2): 521–547, doi:10.5194/tc-12-521-2018.

Groh, A., & Horwath, M. (2021). Antarctic ice mass change products from GRACE/GRACE-FO using tailored sensitivity kernels. Remote Sensing, 13(9), 1736.

Karlsson, N. B., Solgaard, A. M., Mankoff, K. D., Gillet-Chaulet, F., MacGregor, J. A., Box, J. E., ... & Fausto, R. S. (2021). A first constraint on basal melt-water production of the Greenland ice sheet. *Nature Communications*, *12*(1), 3461.

Mottram, R., Hansen, N., Kittel, C., van Wessem, J. M., Agosta, C., Amory, C., ... & Souverijns, N. (2021). What is the surface mass balance of Antarctica? An intercomparison of regional climate model estimates. The Cryosphere, 15(8), 3751-3784.

Rignot, E., J. L. Bamber, M. R. van den Broeke, C. Davis, Y. Li, W. J. van de Berg and E. van Meijgaard. 2008. Recent Antarctic Ice Mass Loss from Radar Interferometry and Regional Climate Modelling. Nature Geoscience 1 (2): 106–110. doi:10.1038/ngeo102.

Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M. J., & Morlighem, M. (2019). Four decades of Antarctic Ice Sheet mass balance from 1979–2017. Proceedings of the National Academy of Sciences, 201812883. doi:10.1073/pnas.1812883116

Wuite, J., Rott, H., Hetzenecker, M., Floricioiu, D., De Rydt, J., Gudmundsson, G. H., Nagler, T., and Kern, M.: Evolution of surface velocities and ice discharge of Larsen B outlet glaciers from 1995 to 2013, The Cryosphere, 9, 957–969, https://doi.org/10.5194/tc-9-957-2015, 2015.