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

D5.1 - Climate Assessment Report (CAR)

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Change Log

Issue	Author	Affected Section	Change	Status
1.0	S. Palmer	All	Document Preparation	

Acronyms and Abbreviations

Acronym	Explanation
AIS	Antarctic Ice Sheet
CAR	Climate Assessment Report
CCI	Climate Change Initiative
DEM	Digital Elevation Model
DInSAR	Differential SAR Interferometry
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DTU	Danmarks Tekniske Universitet
ECV	Essential Climate Variable
ENVEO	Environmental Earth Observation
ERS	European Remote Sensing satellite
ESA	European Space Agency
GFZ	Helmholtz Centre for Geosciences
GLL	Grounding Line Location
GLM	Grounding Line Migration
GMB	Gravimetric Mass Balance
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
IMBIE	Ice Sheet Mass Balance Inter-comparison Exercise
InSAR	Interferometric synthetic-aperture radar
IPCC	Intergovernmental Panel on Climate Change
ISCL	Ice Shelf Coast Line
IV	Ice Velocity
IVC	Ice Velocity Change
MISI	Marine Ice Sheet Instability Hypothesis
REMA	Reference Elevation Model of Antarctica
RMSE	Root-Mean-Square Error
SAR	Synthetic Aperture Radar
SARIn	Synthetic Aperture Radar Interferometry
SEC	Surface Elevation Change
SLC	Single Look Complex
SMB	Surface Mass Balance
SNR	Signal to Noise Ratio

TUDr	Technische Universität Dresden
UCL	University College London
UL	University of Leeds

1 Introduction

1.1 Purpose and Scope

This document provides an updated Climate Assessment Report (CAR) for the Antarctica_Ice_Sheet_cci+ (AIS_cci+) project, in accordance with the contract and SoW [AD2 and AD3]. It builds on the previous CAR published in May 2022 [AD4]. It evaluates the extent to which AIS_cci+ products meet user requirements and assesses their overall quality and utility for climate research, with emphasis on ice-sheet mass balance, ice dynamics variability, and use in model evaluation and process understanding.

The assessment covers the four AIS_cci+ ECV products:

- Surface Elevation Change (SEC)
- Gravimetric Mass Balance (GMB)
- Ice Velocity (IV)
- Grounding Line Location (GLL)

1.2 Document Structure

This document is structured into an introductory chapter followed by 4 chapters focussed on:

Chapter 2: Overview of AIS_cci+ ECV products

Chapter 3: Mass budget of the Antarctic Ice Sheets

Chapter 4: Process studies and dynamical variability of the Antarctic Ice Sheets

Chapter 5: Climate Assessment Report recommendations.

1.3 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	NU-ESA-AISCCI+-SSD-002	Antarctica_Ice_Sheet_cci+ System Specification Document (SSD)	02.11.2025	Version 1
AD2	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
AD3	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
AD4	ST-UL-ESA-AISCCI+-CAR-001	CCI+ PHASE 1 - Climate Assessment Report	04.05.2022	1.0

2 Overview of AIS-cci+ ECV data products and user requirements

The Antarctic Ice Sheet (AIS) is a key component of the climate system and a major source of uncertainty in long-term global sea-level projections. Its contribution to sea-level rise depends in part on whether sections of the ice sheet undergo nonlinear retreat in response to oceanic and atmospheric forcing. Antarctica is therefore highlighted by the IPCC as a major uncertainty in future sea-level change, particularly where processes such as marine ice-sheet instability may accelerate ice loss (Fox-Kemper et al., 2021).

The AIS responds to climate change through multiple processes with contrasting effects on mass balance. Increased atmospheric moisture can enhance snowfall and temporarily increase surface mass input, while ocean-driven thinning of ice shelves can reduce buttressing, accelerate grounded ice flow, and increase ice discharge to the ocean. Observations and modelling studies show that these competing influences can operate simultaneously, so short-term mass gains from anomalous snowfall may coexist with longer-term dynamic mass loss in vulnerable marine sectors.

Concern centres on marine-based parts of West Antarctica and some East Antarctic basins, where grounding-line retreat, ice-shelf thinning and inland dynamic adjustment may trigger 'run-away' ice loss e.g. via the Marine Ice sheet instability (MISI) mechanism. Recent observational and modelling studies continue to reinforce the importance of grounding-zone and ice-shelf processes in controlling Antarctic instability and long-term sea-level commitment (Miles and Bingham 2024; Reed at al., 2024).

Within this context, the ESA Climate Change Initiative (CCI) Antarctic Ice Sheet project provides long-term, openly available climate data records derived from satellite observations for use by the wider scientific community. The project is designed to develop reliable Antarctic datasets for core variables: surface elevation change, grounding line location, ice velocity and mass balance, and to make these records accessible in forms that are usable by climate researchers and modellers (ESA Climate office).

This role is particularly valuable for the climate-modelling community. Converting raw satellite measurements into climate-relevant records requires substantial sensor-specific expertise, geophysical corrections, and careful treatment of uncertainty. By providing standardised Essential Climate Variable products, the AIS CCI framework lowers the technical barrier to using Earth Observation data in model evaluation, forcing, assimilation and process studies. At the same time, this places a strong responsibility on the products themselves: to be genuinely useful for climate applications, they must be accompanied by realistic uncertainty estimates, clear metadata, and guidance on appropriate scales and limitations of use.

A core strength of the CCI approach is its focus on a limited set of Essential Climate Variables that are both observable from space and directly relevant to climate understanding. For Antarctica, this focus is scientifically justified because changes in ice-sheet geometry, grounding-zone migration, ice motion and integrated mass balance together provide a powerful observational basis for monitoring change and constraining models. As research priorities evolve, however, these products need to be reviewed not only for technical quality, but also for how well they support emerging needs in process understanding, model development and climate assessment.

Phase 2 of AIS_cci+ has broadened the original ECV suite by introducing three additional products focused more explicitly on change detection and dynamic monitoring: Ice Velocity Change (IVC), Grounding Line Migration (GLM) and Ice Shelf CoastLine (ISCL). These developments are well aligned with the increasing scientific need to detect early signs of instability, rather than the routine monitoring of the whole Ice Sheet. However, the new products are at different levels of maturity. IVC is currently a prototype under development, GLM is enabled through the grounding-line database but remains dependent on the partly manual GLL workflow, and ISCL has the clearest operational implementation so far, although currently limited to three major ice shelves. Taken together, these new products represent an important strategic extension of AIS_cci+, but remain emerging phase-2 capabilities rather than operational ECVs, so are not evaluated here.

2.1 ECV product descriptions

The Antarctic Ice Sheet CCI project develops long-term, satellite-based climate data records for a set of key geophysical parameters that describe changes in Antarctic ice-sheet geometry, motion, grounding-zone evolution and mass balance. The current AIS_cci+ portfolio includes four core operational products - Surface Elevation Change (SEC), Ice Velocity (IV), Grounding Line Location (GLL), and Gravimetric Mass Balance (GMB). These products are intended to support climate research and model evaluation by providing consistent, openly available records derived from satellite observations.

Surface Elevation Change (SEC)

Surface elevation change is one of the most informative observational products for Antarctic climate research because it records how ice-sheet geometry evolves through time. SEC reflects the combined effects of dynamic thinning or thickening, changes in snowfall and firn processes, and, in some regions, changes linked to subglacial hydrology or grounding-zone adjustment (fig. 1). It is therefore central both to monitoring the ice sheet and to testing whether models reproduce observed patterns of inland thinning, marginal drawdown and regional mass imbalance. The AIS_cci+ SEC product is derived from radar altimetry missions operating since 1991 and is distributed on a 5 km Antarctic polar stereographic grid as a multi-mission series of 5-year mean SEC fields at monthly intervals, together with uncertainty estimates and ancillary layers such as basin identifiers and surface type.

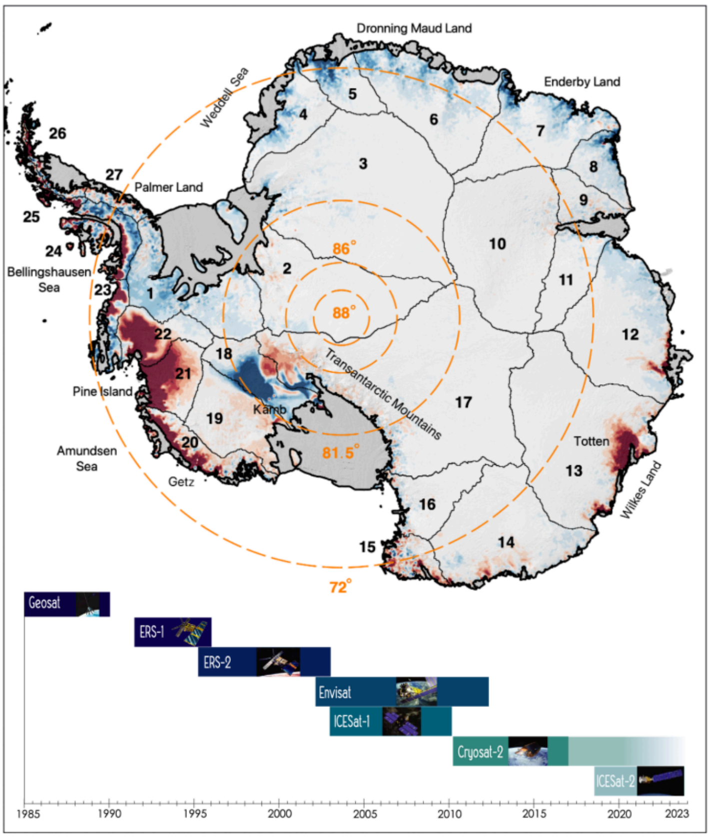

Figure 1: Spatial and temporal coverage of the seven satellite altimetry missions used to produce the elevation change synthesis presented by Nilsson et al. (2022). Concentric dashed circles and labels (orange) indicate orbital limits of each mission (Geosat 72° ; ERS-1, ERS-2, and Envisat 81.5°; ICESat 86°; and CryoSat-2 and ICESat-2 88°). Antarctic drainage basins 1–27 are shown in black. Orbital limit sand drainage basins are plotted over elevation change rates (1992–2020) from Nilsson et al., 2022, with a range of ± 20 cm yr^{-1}(blue indicates positive and red negative changes in elevation). From Nilsson et al. (2022).

Gravimetric Mass Balance (GMB)

Gravimetric Mass Balance provides a direct measure of changes in grounded Antarctic ice mass from time-variable gravity observations. Its main value is that it estimates mass change directly, rather than requiring conversion from elevation or velocity using density assumptions. This makes it especially important for assessing Antarctic contribution to sea-level rise and for identifying large-scale mass anomalies associated with snowfall variability or long-term dynamic loss (fig. 2). The AIS_cci+ GMB products are derived from GRACE (2002-2017) and GRACE-FO (launched in 2018) monthly gravity solutions and are provided both as a gridded product on a 50 km polar stereographic grid and as basin-scale time series. The effective spatial resolution is much coarser than the grid spacing, at roughly 300 km, so the product is most appropriate for basin to continental-scale analyses rather than glacier-scale studies. Recently, the Helmholtz Centre for Geosciences (GFZ) developed the Gravity Information Service (GravIS) portal to facilitate easy accessibility of the GRACE and GRACE-FO results beyond the geodetic community (Dahle et al., 2025). The portal interface is shown in Chapter 5.

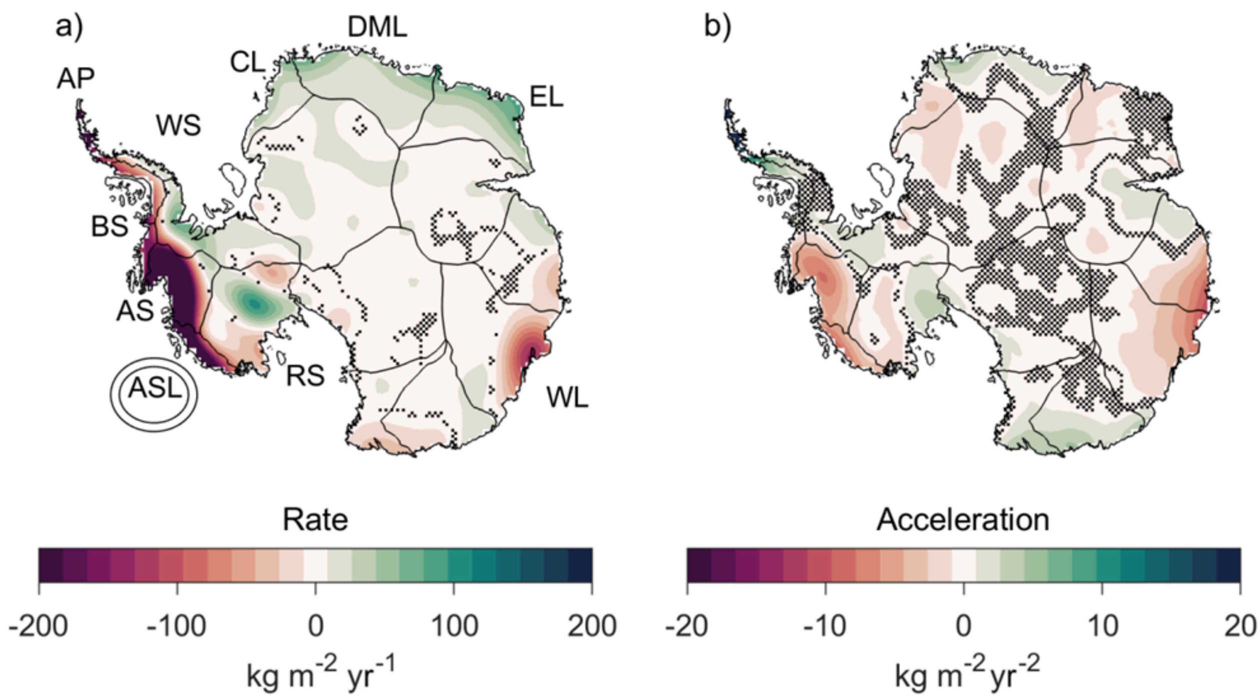

Figure 2: (a) Linear rate and (b) acceleration of AIS mass change (2002–2022) based on univariant regression of the GravIS version of the GMB CCI product. Key Antarctic regions are labelled: Antarctic Peninsula (AP), Bellingshausen Sea (BS), Amundsen Sea (AS), Amundsen Sea Low (ASL), Ross Sea (RS), Wilkes Land (WL), Enderby Land (EL), Dronning Maud Land (DML), Coats Land (CL), and Weddell Sea (WS). Stippling indicates areas not statistically significant (ρ > 0.05). Modified From Ayabilah et al. (2026).

Ice Velocity (IV)

Ice velocity is essential for understanding Antarctic dynamic change because it provides the most direct satellite-based measure of ice flow (fig. 3). While SEC and GMB are sufficient to detect net mass change, IV is needed to determine whether models reproduce that change for the correct dynamical reasons - for example, through acceleration linked to reduced buttressing, grounding-line retreat, or evolving stress conditions. It is also a key input to discharge and input-output estimates of Antarctic mass balance. The AIS_cci+ IV product is based primarily on Sentinel-1 SAR data and is provided as gridded maps of horizontal velocity components, velocity magnitude, vertical displacement relative to a DEM, valid pixel count and uncertainty. According to the current product specification, the main Sentinel-1 product is delivered at 200 m resolution over the Antarctic Ice Sheet margins, with 6-12 day and monthly sampling from 2015 onwards; additional regional products based on SAOCOM and combined SAOCOM/Sentinel-1 acquisitions are also being developed for selected sectors.

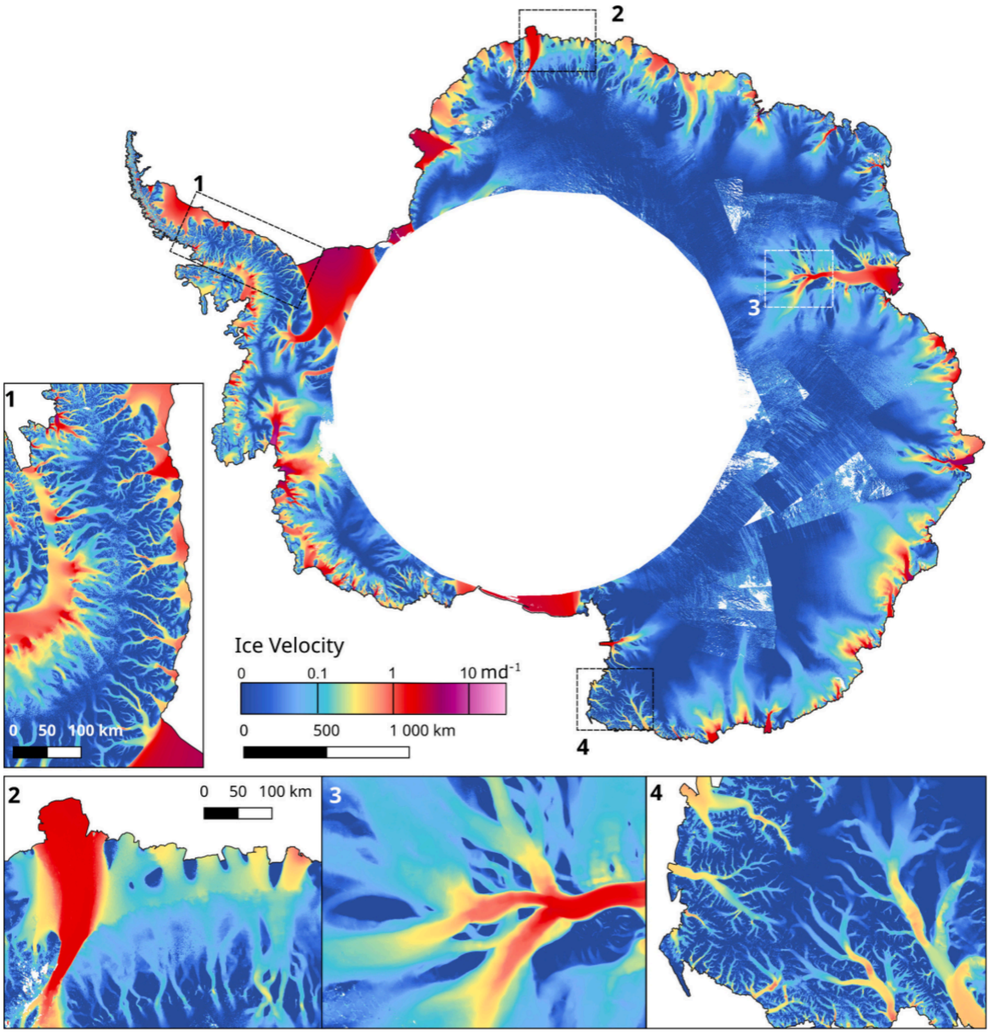

Figure 3: Antarctic Ice velocity derived from Sentinel-1 SAR data of the period 2014-2024. The insets show close-ups of the map as indicated by the numbered boxes. From Wuite et al. (2026).

Grounding Line Location (GLL)

Grounding line location is a key metric for marine ice-sheet stability because it marks the transition between grounded ice and floating ice shelf. Retreat of the grounding line is closely linked to ocean forcing, ice-shelf weakening and the potential for self-sustaining retreat in marine basins. For this reason, GLL is one of the most important observational products for evaluating whether ice-sheet models correctly simulate the mechanisms of Antarctic dynamic change. In AIS_cci+, grounding lines are mapped primarily using double-differential InSAR (DInSAR), which is treated as the most accurate satellite method for identifying the tidal flexure signal associated with grounding-zone position. The current product focuses on major Antarctic outlet glaciers and ice shelves, particularly in dynamically active sectors, and is delivered as vector products derived from SAR data acquired over the period covered by the project. The current phase also includes development towards more automated delineation and a derived Grounding Line Migration (GLM) product, reflecting the increasing need for denser time series of grounding-zone change. In a recent innovative study, the AIS_CCI Grounding Line Location (GLL) dataset was used as training and validation data to train a neural network and automatically delineate grounding lines from DInSAR interferograms (Ramanath et al., 2025; fig. 4).

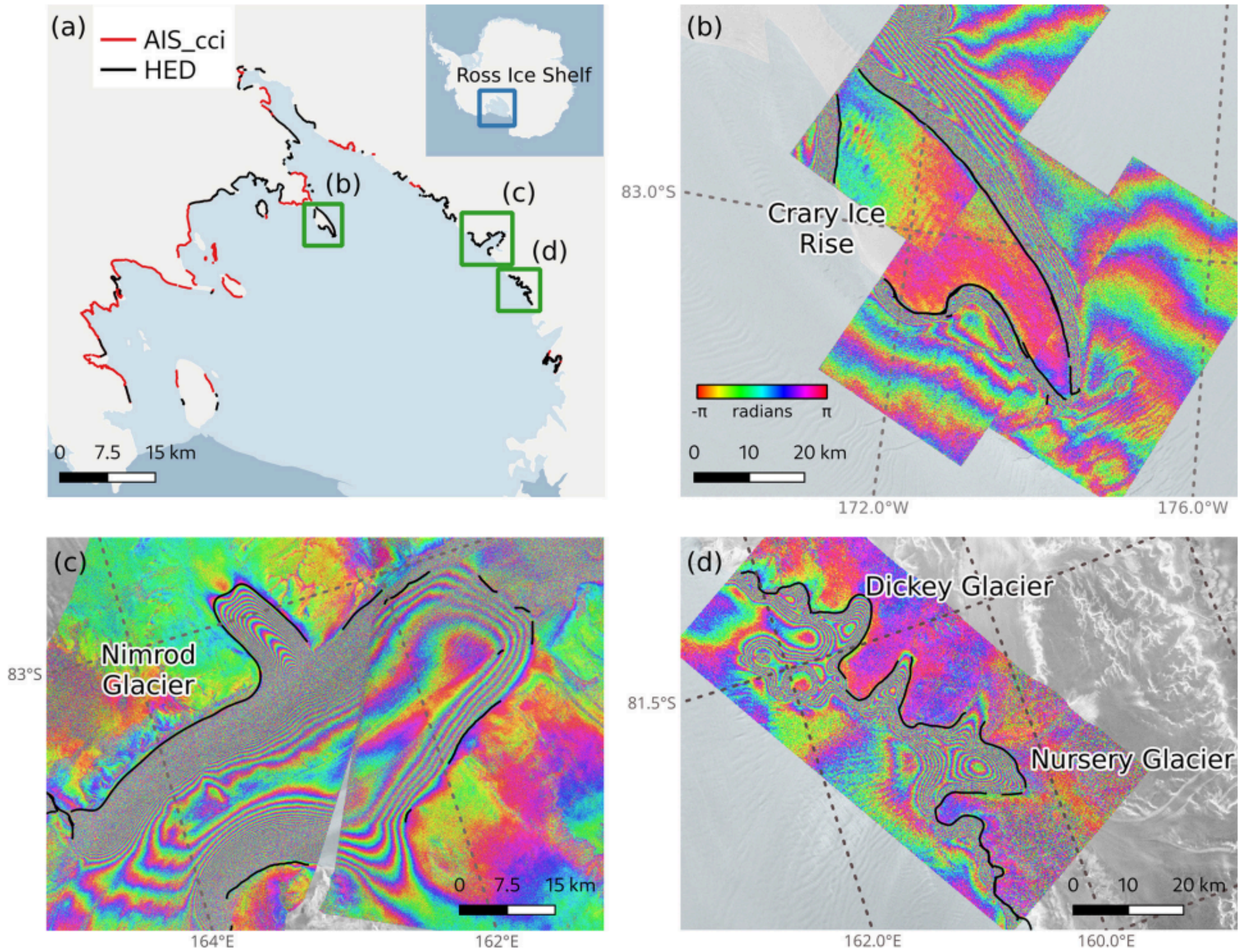

Figure 4: (a) AIS_cci GLL (red) and holistically nested edge detection (HED) trained on the temporal dataset (black) grounding lines for several glaciers situated around the Figure 9. (a) AIS_cci GLL (red) and HED trained on the temporal dataset (black) grounding lines for several glaciers situated around the Ross Ice Shelf (upper left). HED delineations for interferograms over (b) Crary Ice Rise, (c) Nimrod Glacier, and (d) Dickey and Nursery glaciers. The discontinuous GLs for the Nimrod Glacier and Crary Ice Rise are from two spatially overlapping but temporally separate DInSAR interferograms. The interferograms appear brighter in the overlapping regions. From Ramanath et al. (2025).

2.1 Use of ECVs by the community

AIS ECV data products are made available to the community via three portals.

- SEC through the Centre for Polar Observation and Modelling (UK) [https://cpom.org.uk/datasets/];
- GMB through the Technische Universität Dresden (Germany) [data1.geo.tu-dresden.de/ais_gmb]; and
- IV and GLL through ENVEO - ENVironmental Earth Observation IT GmbH (Austria) [cryoportal.enveo.at].

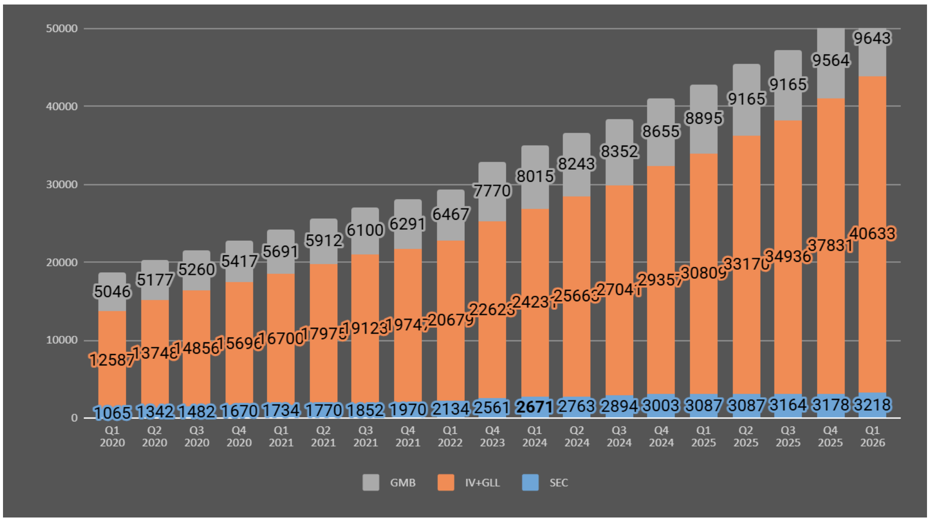

Figure 5: Cumulative visitors to the AIS_CCI data portals over time. Note the gap between Q1 2022 and Q4 2023 which is due to the transition from phase 1 to phase 2 of the project.

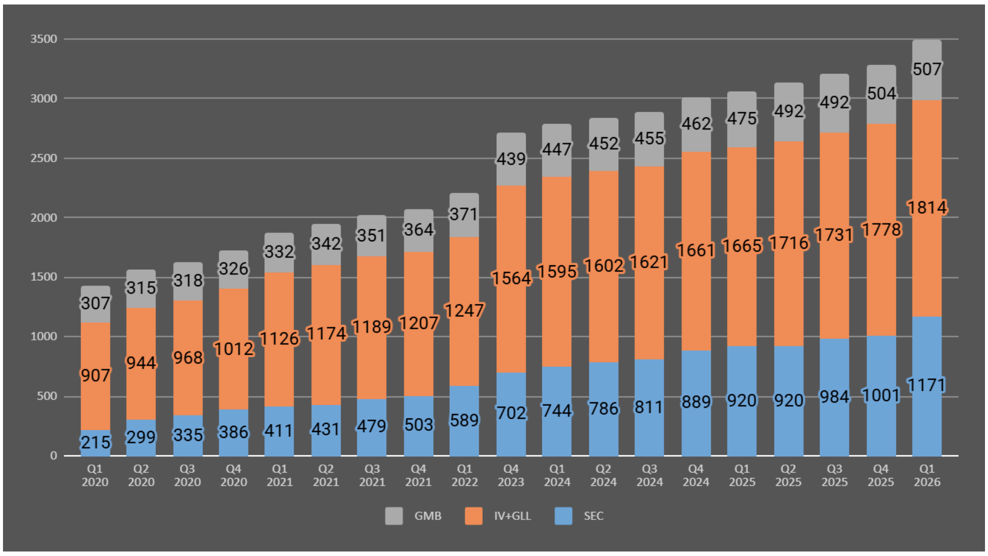

Figure 6: Cumulative downloads of AIS_CCI data over time. Note the gap between Q1 2022 and Q4 2023 which is due to the transition from phase 1 to phase 2 of the project

3 Mass budget of the Antarctic ice sheet

Within the current operational ECV portfolio, the mass budget is constrained primarily by the Surface Elevation Change (SEC) and Gravimetric Mass Balance (GMB) products and is further informed by Ice Velocity (IV) through discharge-based analyses (Otosaka et al., 2023; Davison et al., 2025). Quantifying Antarctic mass change is central to climate research because it determines the ice sheet's contribution to global mean sea-level rise and provides one of the strongest observational tests for models of ice-sheet evolution (Otosaka et al., 2023). Confidence in future projections depends in part on whether models can reproduce the observed recent history of Antarctic mass gain and loss, including both long-term trends and shorter-term variability (Seroussi et al., 2020; Edwards et al., 2021; Payne et al., 2021).

A key point emerging from the literature is that Antarctic mass balance cannot be understood as a single monotonic signal. Instead, it reflects the superposition of contrasting processes operating over different timescales and regions. In some sectors, especially in West Antarctica and parts of the Antarctic Peninsula, sustained dynamic thinning and increased discharge have driven mass loss over recent decades (Davison et al., 2024, 2025; Otosaka et al., 2023). In other sectors, especially in East Antarctica, short-term or episodic mass gain associated with anomalous snowfall has partly offset dynamic loss at broader spatial scales (Kolbe et al., 2026; Näränen et al., 2026). The role of AIS_cci+ products is therefore not simply to quantify net mass change, but to help distinguish these competing contributions and provide climate-relevant records for model evaluation and attribution (Otosaka et al., 2023; Kolbe et al., 2026).

3.1 Continental mass budget of AIS

A useful starting point remains the multi-method mass-budget assessments developed through IMBIE, which reconcile three largely independent approaches: altimetry-based elevation change, gravimetry-based mass change, and the input-output method (Shepherd et al., 2018; Otosaka et al., 2023). These studies established that Antarctica has, on average, lost mass over the satellite era, with the strongest losses concentrated in West Antarctica and the Antarctic Peninsula, while East Antarctica shows smaller and much more uncertain net change (Shepherd et al., 2018; Otosaka et al., 2023; fig 7.). The value of this framework for the CCI context is that it provides the climate-modelling community with reconciled observational evidence rather than requiring users to choose between competing methods (Otosaka et al., 2023).

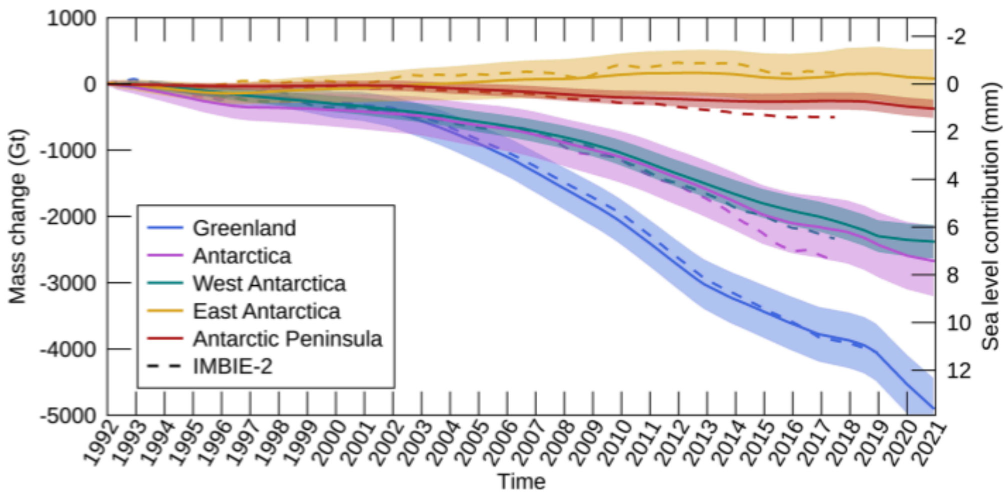

Figure 7: Cumulative ice sheet mass changes in the latest IMBIE assessment presented in Otosaka et al. (2023). The shadings represent the associated uncertainties, and the dashed lines show the previous IMBIE-2 results. From Otosaka et al. (2023)

In the context of AIS_cci+, this integrated view has since been refined in two important ways. First, more recent reconciled assessments of Antarctic and Greenland mass balance have continued to show the utility of combining altimetry, gravimetry and input-output methods to quantify long-term ice-sheet imbalance and sea-level contribution (Otosaka et al., 2023). These studies confirm that mass loss from West Antarctica has remained the dominant Antarctic contribution to sea-level rise, while uncertainty over East Antarctica remains relatively large because the competing influences of snowfall variability, firn change, dynamic imbalance and glacial isostatic adjustment are harder to separate there (Otosaka et al., 2023).

Second, recent work using the AIS_cci+ GMB product has shown that the Antarctic mass budget can depart substantially from the longer-term trend over relatively short periods. In particular, analyses based on the ESA CCI Antarctic Ice Sheet Gravimetric Mass Balance product indicate that the apparent slowdown in Antarctic mass loss after 2020, and even temporary mass gain, was primarily associated with unusually strong snowfall anomalies linked to atmospheric circulation changes and atmospheric-river activity, rather than with any reversal of dynamic ice loss (Kolbe et al., 2026). This is a significant advance because it demonstrates that short-term net mass gain at the continental scale does not necessarily imply stabilisation of dynamically vulnerable sectors. Instead, it reflects the coexistence of episodic surface mass-balance anomalies with ongoing dynamic imbalance (Kolbe et al., 2026; Davison et al., 2025).

This has important implications for how Antarctic mass-budget products are interpreted. The GMB product is especially powerful for identifying continent-scale and basin-scale anomalies in grounded mass, but it does not by itself determine whether those anomalies arise from snowfall, firn adjustment, discharge change or some combination of these (Kolbe et al., 2026; Pan et al., 2025). For that reason, the gravimetric record is most informative when interpreted together with SEC and, where possible, with independent climate and surface mass-balance information (Kolbe et al., 2026; Otosaka et al., 2023).

3.2 SEC, GMB and the separation of dynamic and SMB signals

One of the central scientific challenges in Antarctic mass-budget research is distinguishing between changes caused by surface mass balance and those caused by ice dynamics. SEC and GMB are complementary in this respect. SEC provides high-resolution information on where the ice sheet is thickening or thinning, while GMB provides a direct estimate of net grounded mass change (Shepherd et al., 2019; Otosaka et al., 2023). However, neither product alone can fully partition the signal into snowfall-driven and dynamic contributions (Kappelsberger et al., 2024; Willen et al., 2024).

This issue was addressed in earlier work by combining SEC with regional climate-model output to separate snowfall-related changes from dynamic thickness change (Shepherd et al., 2019) - an approach that remains highly relevant. It demonstrated that some of the largest Antarctic signals are dynamically driven, particularly in West Antarctica, whereas large parts of East Antarctica are more strongly influenced by snowfall variability and associated firn-height changes (Shepherd et al., 2019). This distinction remains crucial for climate-modelling applications because the models used to simulate SMB and those used to simulate ice dynamics differ substantially, and both need to be tested independently (Edwards et al., 2021; Payne et al., 2021).

More recent literature confirms that this separation remains one of the main frontiers for Antarctic product development. Studies using SEC have shown that dynamic thinning can now be tracked more effectively at grounding zones and along major outlet glaciers, while gravimetry-based GMB has proved especially valuable for identifying broad regional anomalies (Davison et al., 2025; Picton et al., 2023; Kolbe et al., 2026). At the same time, competitor studies using firn-aware or inversion-based frameworks have shown that better decomposition of elevation and mass signals is still needed, particularly in East Antarctica and regions with strong interannual snowfall variability (Kappelsberger et al., 2024; Willen et al., 2024).

For the AIS_cci+ programme, this means that SEC and GMB should not be viewed as competing measurements of the same quantity, but as jointly necessary products. SEC contributes spatial detail and sensitivity to localised dynamic evolution; GMB contributes a direct large-scale mass constraint. Together they provide a much stronger basis for interpretation than either can alone (Sasgen et al., 2019; Otosaka et al., 2023).

3.3 Development of gravimetric mass-balance products and uncertainty

The development of the AIS_cci+ GMB product has placed strong emphasis on uncertainty treatment, scale-appropriate interpretation and Antarctic-specific processing. Earlier intercomparison work on GRACE gravimetry products highlighted how strongly Antarctic mass-balance estimates can depend on processing choices, including filtering strategy, spherical harmonic treatment, leakage correction, glacial isostatic adjustment correction and basin averaging (Groh et al., 2019). This work was important because it demonstrated that gravimetric uncertainty is not only a matter of instrumental noise, but also of methodological choice (Groh et al., 2019).

Subsequent development of the AIS_cci+ GMB product addressed this by adopting Antarctic-specific approaches based on tailored sensitivity kernels and basin-scale products designed to reduce leakage and improve interpretability (Horwath, 2021; Dahle et al., 2025). Recent studies using the AIS_cci+ gravimetric product have shown that these developments make the dataset especially useful as an end-user Antarctic mass-balance product (Kolbe et al., 2026; Naranen et al., 2025). Compared with raw or generic GRACE/GRACE-FO solutions, the added value of the AIS_cci+ GMB dataset lies in providing a science-ready Antarctic record that can be used directly in glaciological and climate studies (Kolbe et al., 2026; Naranen et al., 2025).

At the same time, comparison with competitor gravimetry products from CSR, JPL and GSFC shows that uncertainty related to processing-centre choice remains important. Studies based on those products often focus explicitly on solution spread and robustness across centres, while AIS_cci+ GMB studies have tended to focus more on Antarctic interpretation (Pan et al., 2025; Jiao et al., 2023; Dahle et al., 2025). The AIS_cci+ GravIS product is especially valuable for user-ready Antarctic analysis, but continued intercomparison with alternative gravimetry products remains important for quantifying methodological uncertainty and maintaining confidence in long-term trends and short-term anomalies (Pan et al., 2025; Jiao et al., 2023).

3.4 Combining SEC and GMB

A recurring theme in Antarctic mass-budget studies is that SEC and GMB provide complementary information at different scales. Gravimetry is strongest at broader scales, where it offers a direct estimate of mass change. Altimetry is stronger at finer spatial scales, where it resolves localised thinning and thickening associated with dynamic or SMB-related changes (Sasgen et al., 2019; Otosaka et al., 2023). Earlier work demonstrated the value of combining these two datasets into a single framework that exploits the broad-scale strength of gravimetry and the finer spatial detail of altimetry (Sasgen et al., 2019).

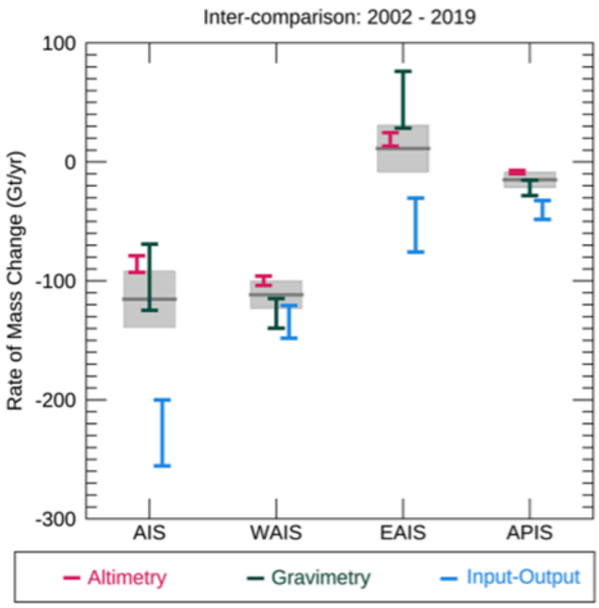

Figure 8: IMBIE inter-comparison of rates of ice sheet mass balance of the Antarctic Ice Sheet (AIS), West Antarctic Ice Sheet (WAIS), East Antarctic Ice Sheet (EAIS) and Antarctic Peninsula Ice Sheet (APIS) over the period 2002-2019 as derived from the altimetry, gravimetry and input-output techniques. The coloured bars represent the rates of mass balance and uncertainties in the aggregated technique time series. The grey box represents the rate of mass balance of the final reconciled IMBIE assessment (Otosaka et al., 2023). The horizontal line in the middle of the box shows the reconciled rate of the mass balance, and the height of the box represents its associated uncertainty. Modified from Otosaka et al. (2023).

Recent studies show that many of the most important Antarctic signals involve both broad and local components: for example, a basin-wide or continental snowfall anomaly superimposed on strongly localised dynamic thinning near grounding lines or marine outlets (Kolbe et al., 2026; Davison et al., 2025). In such cases, neither SEC nor GMB alone gives a complete picture. A combined interpretation allows users to distinguish widespread regional mass anomalies from focused dynamic imbalance (Sasgen et al., 2019; Otosaka et al., 2023; fig. 8).

For climate-model evaluation, this is particularly important. Models should be expected not only to reproduce net Antarctic mass change, but also to capture whether that change is expressed as widespread snowfall-driven thickening, dynamic drawdown concentrated at outlet glaciers, or a combination of both (Edwards et al., 2021; Payne et al., 2021). The joint use of SEC and GMB therefore provides a more stringent and more informative test than either product alone (Sasgen et al., 2019).

3.5 Applications of AIS mass-budget products

The mass-budget products developed within AIS_cci+ contribute directly to wider assessments of global ice loss, sea-level budget closure and Earth-system change, and they provide observational constraints for climate and ocean modelling (Slater et al., 2021; Horwath et al., 2022).

At the global scale, Antarctic SEC and GMB records have contributed to assessments of total ice loss from the Earth system and to efforts to close the global sea-level and ocean-mass budgets (Slater et al., 2021; Horwath et al., 2022). One of the major advances in these broader studies has been improved uncertainty characterisation across the contributing terms, allowing better evaluation of whether observed sea-level rise can be reconciled with contributions from glaciers, ice sheets, land water storage and ocean steric change (Horwath et al., 2022). Within this context, Antarctic mass-budget observations are indispensable, because they represent one of the largest and most uncertain contributors to long-term sea-level rise (Horwath et al., 2022).

Most importantly for climate projections, Antarctic mass-budget records have played a central role in model intercomparison exercises and in assessments used by the IPCC (Seroussi et al., 2020; Edwards et al., 2021; Payne et al., 2021). Recent generations of ice-sheet projections have increasingly relied on observational products such as SEC, GMB and reconciled mass-balance time series to assess whether model initial conditions and historical simulations are realistic (Seroussi et al., 2020; Edwards et al., 2021). This is particularly important because Antarctic forcing is highly variable in time, and because the ice sheet responds through at least two competing pathways: increased snowfall in a warmer atmosphere, and increased dynamic discharge driven by ocean-forced weakening of ice shelves and grounding-zone retreat (Edwards et al., 2021; Payne et al., 2021). Observational products that help separate these pathways are therefore critical (Shepherd et al., 2019; Edwards et al., 2021).

Recent comparisons between observed and projected ice-loss trajectories have reinforced the importance of this distinction. Observational evidence suggests that the balance between snowfall-driven mass gain and dynamic mass loss has not always been represented accurately in earlier generations of projections (Slater et al., 2020). This further underlines the value of AIS_cci+ products that help distinguish net mass change from its underlying causes (Slater et al., 2020; Edwards et al., 2021).

3.6 Implications for climate research and model evaluation

For the climate-modelling community, the main value of AIS_cci+ mass-budget products lies in the fact that they support progressively more demanding tests of Antarctic model performance. At the most basic level, models should reproduce the sign and magnitude of net mass change at continental and basin scales (Otosaka et al., 2023). At a more demanding level, they should also reproduce the broad regional pattern: strong loss in West Antarctica, much smaller and more uncertain net change in East Antarctica, and pronounced variability associated with accumulation anomalies (Otosaka et al., 2023; Kolbe et al., 2026). At the most demanding level, models should correctly partition observed mass changes into snowfall-related and dynamically driven components (Shepherd et al., 2019; Edwards et al., 2021).

The literature reviewed here suggests that AIS_cci+ products are increasingly able to support that more demanding level of evaluation. SEC provides the spatial pattern of geometric response; GMB provides the large-scale grounded mass signal; IV helps quantify dynamic discharge and acceleration; and in principle GLL helps identify the grounding-zone retreat associated with marine instability (Davison et al., 2025; Picton et al., 2023; Kolbe et al., 2026). The mass-budget chapter therefore sits at the centre of the wider AIS_cci+ portfolio: it is where the different ECVs most clearly converge on a common climate question, namely how and why Antarctic ice loss is changing (Otosaka et al., 2023; Davison et al., 2025).

3.7 Summary

The recent literature focussed on understanding how net mass change varies across Antarctica (Otosaka et al., 2023), how short-term snowfall-driven gain interacts with longer-term dynamic loss (Kolbe et al., 2026; Davison et al., 2025), how SEC and GMB can be used together to strengthen interpretation (Sasgen et al., 2019; Otosaka et al., 2023), and how mass-budget observations can be translated into more effective tests of climate and ice-sheet models (Edwards et al., 2021; Payne et al., 2021).

Within this context, AIS_cci+ SEC and GMB products remain central. SEC provides the spatially detailed record of thickness change that reveals where dynamic imbalance is occurring and how it evolves through time (Davison et al., 2025; Picton et al., 2023). GMB provides the integrated grounded mass signal that anchors Antarctic change in a sea-level context and identifies continent-scale anomalies (Kolbe et al., 2026; Otosaka et al., 2023). Used together, and in combination with IV and climate-model output, they provide a robust basis for monitoring Antarctic change and constraining projections of future sea-level rise (Otosaka et al., 2023; Davison et al., 2025; Kolbe et al., 2026).

4 Investigating Antarctic ice sheet processes

An important strength of the AIS_cci+ project is that it provides ECVs that help explain the processes driving mass ice sheet mass change. While SEC and GMB are central for quantifying mass balance, the addition of Ice Velocity (IV) and Grounding Line Location (GLL) makes it possible to examine the mechanisms linking ice-shelf change, grounding-line retreat, glacier acceleration and inland dynamic drawdown. Used together, these products allow much more demanding tests of process understanding than any single variable can provide.

The recent literature shows that this multi-ECV approach is particularly valuable in three areas. First, it helps identify whether observed thinning is primarily dynamic or surface-mass-balance driven. Second, it allows changes in ice flow and grounding-line position to be linked to ocean forcing, buttressing loss and marine instability. Third, it provides insight into shorter-timescale processes, including seasonal flow variability, evolving fracture and shear-margin weakening, and subglacial hydrology. In this sense, AIS_cci+ products are not only climate indicators, but also tools for investigating the physical mechanisms responsible for Antarctic change.

4.1 Grounded ice: dynamics imbalance and inland response

Recent studies have shown particularly clearly how combinations of SEC, IV and GLL can be used to diagnose dynamic imbalance in grounded Antarctic glaciers. A strong example is provided by Davison et al. (2024), who documented a widespread increase in discharge from glaciers of the western Antarctic Peninsula since 2018. Their analysis combined time-varying discharge estimates with updated thickness information and showed that the recent increase in mass loss was concentrated at glaciers exposed to favourable ocean access, indicating a coherent regional dynamical response rather than isolated local change. This is important because it demonstrates how AIS_cci+-type SEC and IV products can reveal externally forced dynamic reorganisation at regional scale, rather than simply documenting thinning after the fact.

A related advance is provided by Davison et al. (2025), who used time-evolving ice thickness and multi-source velocity data to estimate Antarctic grounding-line discharge from 1996 to 2024 (fig. 9). This study shows that SEC and IV together can move beyond descriptive monitoring and act as dynamic constraints on Antarctic mass loss. By allowing thickness at flux gates to evolve through time, the study captured an important part of the dynamic response of outlet glaciers to sustained thinning, especially in West Antarctica. The wider significance is that process studies of Antarctic change increasingly depend on combining geometry and motion explicitly, rather than treating them separately.

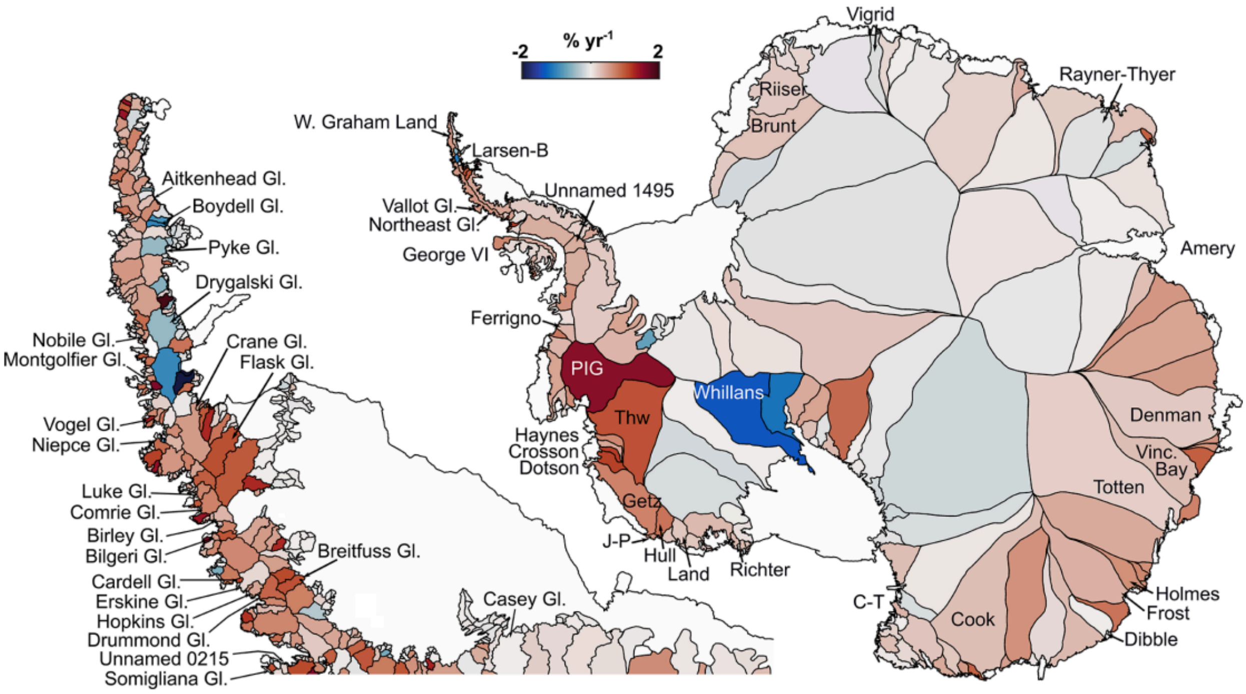

Figure 9: Basin-scale grounding line discharge trends from 1996–2024. Overview of grounding line discharge trends from 1996 through 2024 as a percentage of the median discharge in each drainage basin. Some basin names have been shortened for display purposes: Vinc. Bay is Vincennes Bay, PIG is Pine Island Glacier, Thw is Thwaites, Riiser is Riiser Larsen, C-T is Campbell–Tinker, and J-P is Jackson–Perkins. From Davison et al. (2025)

East Antarctica, which has often been regarded as more stable, also features prominently in recent process studies. Picton et al. (2023) showed that Vanderford Glacier in Vincennes Bay experienced extensive grounding-line retreat, acceleration and thinning over recent decades, identifying it as one of the most dynamically responsive glaciers in East Antarctica. By combining GLL, SEC and IV evidence, the study linked glacier retreat to ocean access and bed geometry and showed how dynamic imbalance can develop in marine-based East Antarctic sectors as well as in the more widely studied Amundsen Sea region. This is an important reminder that process studies of Antarctic change should not be confined to West Antarctica alone.

A similar theme appears in Dong et al. (2025), who examined neighbouring glaciers on the western Antarctic Peninsula and showed that apparently similar glaciers can respond very differently to comparable atmospheric and oceanic forcing. Their analysis used grounding-line, calving-front, elevation and velocity information to show that glacier response depends strongly on local geometry, sea-ice conditions and ocean access. Although this study relied partly on alternative grounding-line methods rather than directly on the ESA CCI GLL product, it is highly relevant to the process agenda of AIS_cci+: it demonstrates that Antarctic process understanding depends critically on combining different observational constraints and on resolving glacier-specific controls rather than assuming spatially uniform behaviour.

4.2 Seasonal and short-timescale changes in ice dynamics

One of the clearest recent advances in Antarctic process studies is the move toward resolving seasonal and short-timescale variability in ice flow. Here the AIS_cci+ IV product has been especially important. Boxall et al. (2022) provided the first evidence for seasonal speed-up in grounded ice flowing into George VI Ice Shelf, showing that summer acceleration near the grounding line can be resolved from monthly Sentinel-1 velocity fields. This is a significant development because it demonstrates that some Antarctic outlet systems respond on seasonal timescales, not only over years to decades.

This short-timescale perspective has been extended by studies of fracture and evolving ice-shelf structure. Zinck et al. (2025) used monthly velocity data to investigate the evolution of a developing channel on George VI Ice Shelf and showed that subtle changes in velocity and divergence can reveal localised weakening before major structural change becomes visually obvious. This illustrates one of the distinctive strengths of high-cadence IV data in process studies: they allow researchers to move from simple change detection toward identification of precursors to instability.

A related example is Parsons et al. (2024), who used monthly velocity fields in combination with modelling to assess the buttressing effect of fast ice and mélange at Crane Glacier. Their results showed that the loss of this frontal resistance altered the local stress regime and affected glacier flow, highlighting the importance of short-lived but mechanically significant frontal conditions. This kind of study is especially valuable because it demonstrates that AIS_cci+-type velocity products are not only observational records but can also act as direct constraints in process-based modelling.

4.3 Subglacial hydrology and basal conditions

Not every important Antarctic process is visible directly at the surface, but SEC has increasingly made it possible to infer some of them. A particularly important example is Wilson et al. (2025), who used a decade of CryoSat-2 elevation change to detect 85 previously unknown active subglacial lakes in Antarctica (fig. 10). Their study showed that uplift and subsidence patterns can be used to identify lake filling and drainage, quantify associated volume changes, and reveal hydrologically connected lake systems.

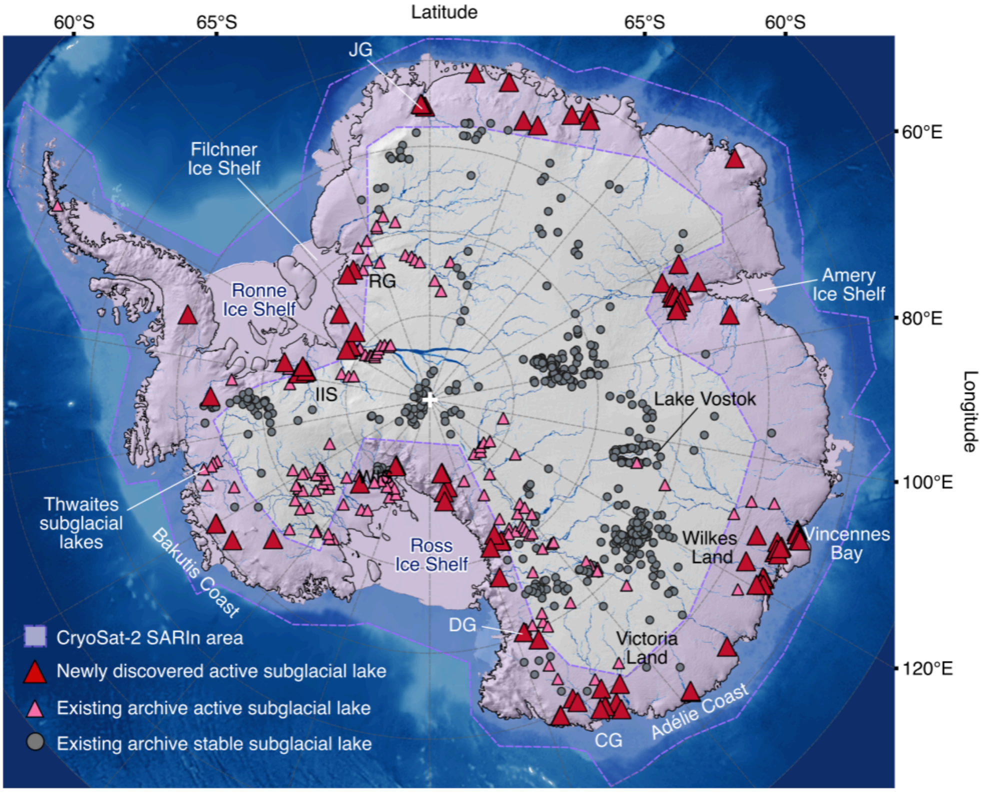

Figure 10: Antarctic subglacial lake inventory, with 85 lakes identified by Wilson et al. (2025) (red triangles). CryoSat-2 SARIn mode data acquisition region (2015) is illustrated around the continent margins (purple shaded area). Existing inventory subglacial lakes are also shown, divided into those derived from satellite studies (pink triangles) and RES surveys (grey circles). Background image is the CryoSat-2 digital elevation model greyscale virtual hill shade separated from ocean bathymetry (blue background) by the ice sheet grounding line (solid black line), overlain with modelled subglacial water routing in blue. Glacier and Ice Stream names are abbreviated: Jutulstraumen Glacier (JG), Cook Glacier (CG), David Glacier (DG), Institute Ice Stream (IIS) and Recovery Glacier (RG). From Wilson et al. (2025).

This is important because it links SEC to basal hydrology and, potentially, to ice dynamics. Subglacial water affects basal traction and may influence how changes initiated near grounding zones or ocean-forced margins are transmitted inland. The study also demonstrates that Antarctic process studies increasingly depend on reading SEC not just as a thinning map, but as an integrated signal of multiple physical processes, including those at the bed.

The importance of this perspective is reinforced by Freer et al. (2024), who showed that drainage of Engelhardt Subglacial Lake West was coincident with grounding-line retreat and ungrounding near the Ross Ice Shelf. Although their study relied on local DInSAR and altimetry analysis rather than the standard GLL product alone, it provides an excellent example of the kind of event-scale process study that the broader AIS_cci+ ECV suite should increasingly support. It also highlights that some of the most informative Antarctic processes occur on local and episodic scales that require combining standard ECV products with targeted higher-frequency observations.

4.4 Ice shelves, buttressing, weakening and fracture

Changes in Antarctica's floating ice shelves are central to process studies of the grounded ice sheet because they control how strongly upstream ice flow is buttressed. Recent work discussed earlier in this review shows that the direct use of AIS_cci+ products over ice shelves has been less extensive than for grounded ice, but still highly informative in selected studies.

The most developed examples in the uploaded literature are studies of velocity and structural weakening. Parsons et al. (2024) showed how changes in frontal conditions at Crane Glacier altered the local buttressing regime. Zinck et al. (2025) demonstrated that high-resolution monthly velocity and divergence fields can reveal evolving structural weakness within George VI Ice Shelf (fig. 11). These studies suggest that IV is especially valuable for process studies of ice shelves where the main concern is stress transmission, local damage evolution and the coupling between shelf weakening and upstream flow.

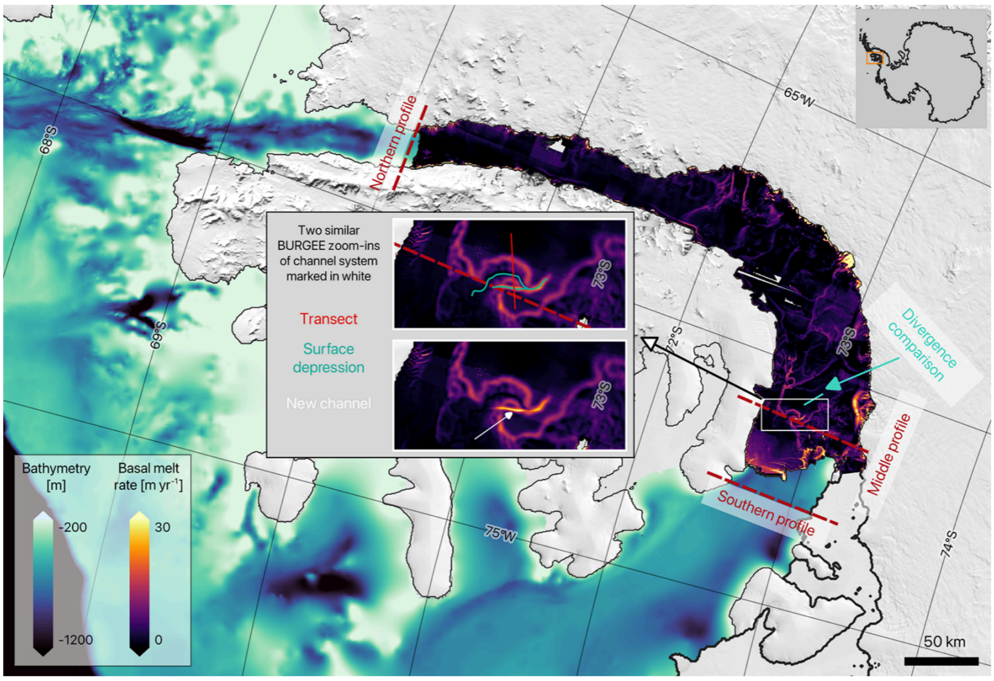

Figure 11: A map of George VI Ice Shelf) with basal melt rates estimated by Zinck et al. (2025). Bathymetry, grounding line and ice shelf extent from BedMachineV3 (Morlighem et al., 2020). Two similar zoom-ins of the highly channelized area marked by the white square show BURGEE melt rates. The upper zoom-in further shows the approximate location of the surface depression of the old and new channels in year 2016 in teal. The lower zoom-in allows for better visualisation of the melting within the channel with the new channel pointed out by the white arrow. From Zinck et al. (2025).

Complementary evidence comes from the wider literature discussed in our earlier comparison work. For example, competitor studies such as Paolo et al. (2023) have shown how surface-elevation and thickness-change observations can be used to infer changing basal melt rates and widespread slowdown in thinning across West Antarctic ice shelves. That work is useful context because it highlights a current imbalance in the AIS_cci+ literature: process studies of grounded-ice dynamics are stronger than direct process studies of floating shelves. This remains an important area for future development, particularly if SEC, IV and ice-shelf coastline products can be integrated more systematically.

4.5 Grounding lines as indicators of stability

Grounding-line position remains one of the most informative indicators of marine ice-sheet stability. Recent studies in the GLL literature confirm that grounding-line retreat is not merely a geometric change, but a physically significant signal of evolving stress balance, reduced buttressing and potentially unstable retreat.

Picton et al. (2023) provide the clearest recent example of direct scientific use of GLL in a process context. Their study of Vanderford Glacier combined grounding-line retreat, thinning and velocity increase to show how marine instability may be developing in an East Antarctic sector previously considered less dynamic. The strength of this paper lies in showing that GLL is most valuable when used together with SEC and IV, rather than as an isolated boundary product.

Ramanath et al. (2025) contribute in a different but strategically important way. By using the ESA CCI grounding-line archive as training data for automated delineation from DInSAR, they show that the GLL dataset is not only a scientific product but also part of the infrastructure needed for future process studies. Improved automation should eventually allow denser grounding-line time series, which would make the product much more useful for studying process timescales shorter than the multi-year intervals that have often characterised Antarctic grounding-line mapping.

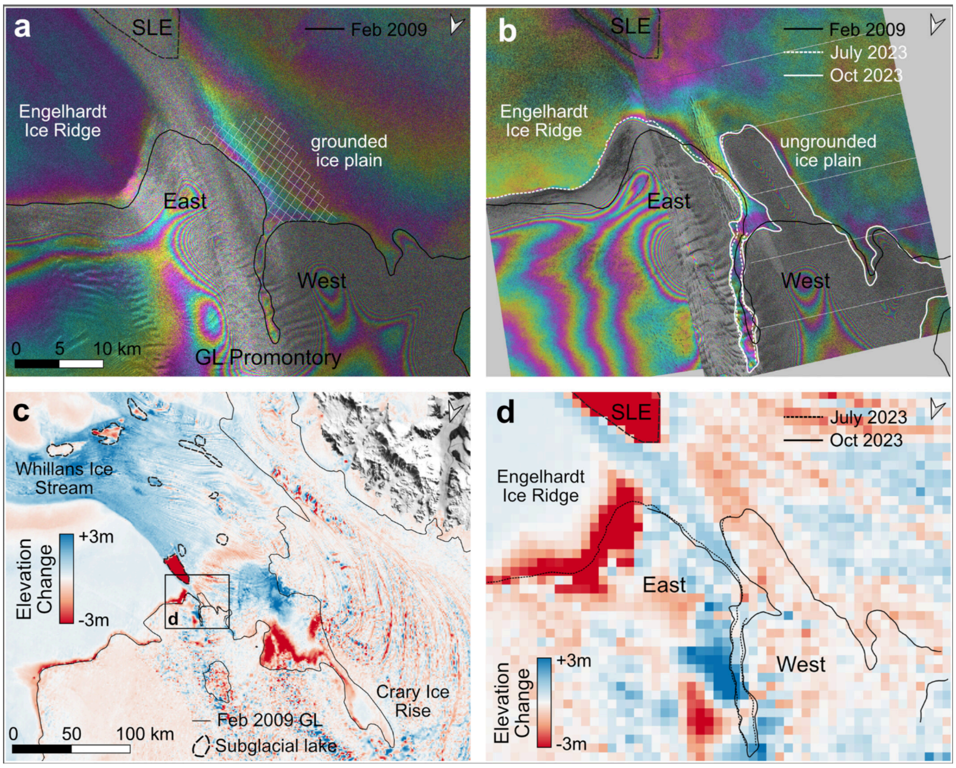

Figure 12: GL migration and surface elevation change downstream of SLE, 2009–24. (a) February 2009 RADARSAT-2 DInSAR and derived GL (blackline)showing the east and west embayment and central grounded promontory. White hashed area shows the approx. location of the grounded ice plain. (b) TerraSAR-X DInSAR and derived GLs from July to October 2023 (white dashed and solid lines, respectively). (c) ICESat-2 ATL15 gridded surface elevation change across the wider Gould Coast, 2019–24. (d) Zoom of (c) over the same region as (a and b) showing the 2023 GL positions. From Freer et al. (2024).

At the same time, the literature also shows where GLL products remain limited. Dong et al. (2025) found that standard DInSAR-based products may be less effective for small, fast-flowing Antarctic Peninsula glaciers, while Freer et al. (2024) showed that event-scale retreat and ungrounding require more targeted local analysis (fig. 11). These studies do not weaken the value of GLL; rather, they define the conditions under which standard products are sufficient and where complementary observations are still necessary.

4.6 Implications for process understanding and model evaluation

Taken together, the recent literature shows that the AIS_cci+ suite is increasingly valuable for process studies because it can trace linked chains of change. SEC reveals where the ice sheet is thinning or thickening; IV shows whether flow is accelerating or decelerating; GLL indicates whether the grounding zone is retreating; and GMB places these changes in a broader mass-balance context. The most powerful studies are those that combine several of these ECVs to move from observed change to process interpretation.

This is especially important for climate and ice-sheet modelling. Models should not only reproduce Antarctic mass loss but should do so for the correct physical reasons. The studies reviewed here show that recent observations now provide much better tests of whether models capture the interactions between ocean forcing, ice-shelf weakening, grounding-line retreat, glacier acceleration, inland drawdown and short-term climate-driven mass anomalies. In this sense, process studies are not separate from mass-budget studies; they are how mass-budget change becomes physically interpretable.

4.7 Summary

The recent literature shows that process studies of the Antarctic Ice Sheet are becoming increasingly sophisticated and increasingly dependent on combinations of AIS_cci+ products. The strongest recent advances include:

- identifying regional dynamical imbalance and increased discharge in West Antarctica and the Antarctic Peninsula (Davison et al., 2024, 2025);
- detecting extensive grounding-line retreat and marine instability in vulnerable East Antarctic glaciers (Picton et al., 2023);
- resolving seasonal and short-timescale changes in Antarctic flow using monthly velocity data (Boxall et al., 2022; Parsons et al., 2024; Zinck et al., 2025);
- and revealing active subglacial hydrology and its potential dynamical significance (Wilson et al., 2025; Freer et al., 2024).

Overall, these studies reinforce the value of AIS_cci+ as more than a monitoring programme. Its greatest scientific potential lies in enabling a process-based understanding of Antarctic change, where geometry, flow, grounding-zone evolution and mass balance are interpreted together rather than in isolation.

5 Climate Assessment Report recommendations

5.1 General recommendations

The AIS_cci+ project has delivered a valuable suite of Earth Observation products to the scientific community working on Antarctic change, sea-level rise and climate-model evaluation. The portfolio now extends well beyond simple monitoring of ice-sheet state and includes products that are demonstrably useful for process studies, model benchmarking and broader climate assessments. Across the literature reviewed here, the AIS_cci+ products are shown to be scientifically valuable, widely applicable and, in several cases, unique because they provide Antarctic-focused, climate-ready records that would otherwise require substantial specialist processing to assemble and interpret (Otosaka et al., 2023; Davison et al., 2025).

A major strength of the programme is that it provides a complementary observing framework rather than a set of isolated variables. SEC, GLL, IV and GMB each contribute different information about Antarctic change, but their real scientific value emerges most clearly when they are interpreted together. SEC provides the spatial expression of thinning and thickening; IV captures the kinematic response of the ice sheet; GLL identifies grounding-zone retreat and marine instability; and GMB provides the integrated grounded-mass signal needed for sea-level assessment. This combined framework is increasingly important for climate research because it allows users not only to quantify Antarctic change, but also to test whether models reproduce the correct physical pathways leading to that change (Picton et al., 2023; Kolbe et al., 2026).

The AIS_cci+ products have also supported more innovative developments that go beyond the provision of individual ECVs. Particularly important examples include the reconciliation of multiple mass-balance methods into coherent long-term records, the use of SEC to distinguish dynamic from surface-mass-balance contributions, and the increasing use of labelled datasets such as the GLL archive to support automated GLL detection using deep learning approaches (Otosaka et al., 2023; Ramanath et al., 2025). These higher-level developments are especially valuable for climate assessment because they translate technically complex observational records into more directly usable forms for the wider research and modelling communities.

Looking ahead, three overlapping but distinct uses of the AIS_cci+ products can be identified. The first remains the original and most important: support for the climate and ice-sheet modelling community. This includes users of stand-alone ice-sheet models, ice-ocean models, regional climate-ice-sheet systems and increasingly coupled Earth system models. For this community, the key requirement is a set of clearly defined products with realistic uncertainties and sufficient metadata to allow meaningful model evaluation. In this context, there is strong value in providing a single, well-characterised product for each variable wherever possible, or at least a clearly signposted recommended reference product supported by transparent uncertainty information. This is particularly important where multiple observational methods exist for the same physical quantity, as in the case of mass balance or grounding-line position (Otosaka et al., 2023; Pan et al., 2025).

The second major use is in monitoring and understanding present-day sea-level rise. Here the emphasis is less on gridded products as such, and more on integrated estimates of Antarctic mass change, discharge and their uncertainty. For this community, GMB and reconciled mass-balance products are especially important, but their interpretation depends strongly on how data gaps are handled, how basin-scale integration is performed, and how gravimetry, altimetry and discharge methods are reconciled. This suggests continued value in developing higher-level Antarctic synthesis products within or alongside AIS_cci+, especially where they support broader assessments of the global sea-level and ocean-mass budgets (Horwath et al., 2022; Otosaka et al., 2023).

A third use, which is likely to grow in importance, is the role of AIS_cci+ products as indicators of emerging instability and potential early warning of high-end sea-level contributions. Grounding-line retreat is the clearest current example. GLL is highly relevant as a warning indicator because rapid inland retreat in marine basins is one of the strongest observational signatures of destabilisation. However, the literature reviewed here also suggests that early warning should not be understood in terms of GLL alone. SEC can reveal inland propagation of drawdown; IV can detect seasonal and decadal acceleration; and ice-shelf-focused products or derived metrics may help identify weakening, rifting and changing buttressing before large discharge anomalies are fully established (Boxall et al., 2022; Parsons et al., 2024; Zinck et al., 2025; Picton et al., 2023). Therefore, a key recommendation is that the new ‘phase 2’ ECVs: Ice Velocity Change (IVC); Grounding Line Migration (GLM); and Ice Shelf Coast Line (ISCL) should be treated as high-priority strategic developments. These products address an important gap in the original ECV suite by focusing more directly on rates of change, dynamic evolution and potential early signs of instability. However, they are currently at different stages of development: IVC remains a prototype, GLM is limited by the cadence and partial automation of the underlying grounding-line workflow, and ISCL has the clearest operational implementation but is still restricted to a small number of major ice shelves. Future development should therefore prioritise improving automation, increasing temporal density, broadening spatial coverage and clarifying uncertainty and use-case guidance, so that these new products can evolve from promising demonstrations into fully operational climate-quality datasets with clear value for model evaluation, process studies and early warning of rapid Antarctic change.

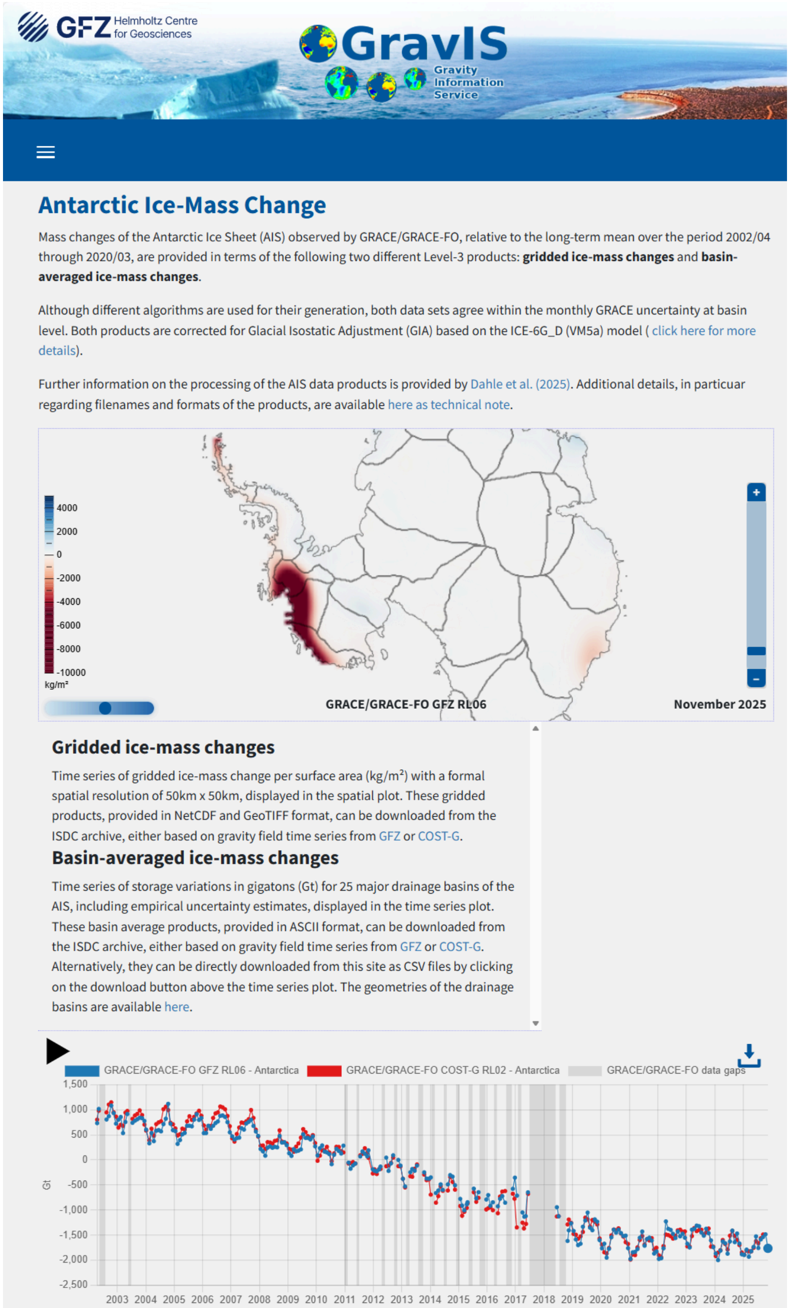

Figure 13: GFZ GravIS web portal for Antarctic Ice-Mass change

Overall, the products provided by AIS_cci+ are of high quality and well aligned with the needs of the target communities. The evidence reviewed suggests that SEC and IV are currently the most mature for dynamic climate-research applications. SEC has moved beyond simple elevation-change mapping and now supports dynamic discharge estimation, regional instability studies and subglacial hydrology detection (Davison et al., 2025; Wilson et al., 2025). IV has become especially important for resolving short-term and seasonal Antarctic flow variability, particularly since the Sentinel-1 era (Boxall et al., 2022; Parsons et al., 2024; Wuite et al., 2026). GLL is scientifically very valuable, especially for studies of marine instability, but remains less mature in terms of temporal density, ease of use and applicability in small or rapidly changing glacier systems (Picton et al., 2023; Ramanath et al., 2025). GMB is highly valuable for Antarctic-wide and basin-scale mass-balance studies, especially in the context of sea-level rise, but is intrinsically less informative for fine-scale process attribution and depends more strongly on auxiliary products for interpretation (Kolbe et al., 2026; Pan et al., 2025).

Several product-development recommendations follow from this assessment. First, the AIS_cci+ portfolio would benefit from being developed more explicitly as an integrated observing system rather than as a set of separate ECVs. The strongest studies in the reviewed literature are those that combine SEC, IV, GLL and GMB to trace linked chains of change from forcing to response. This suggests a need for greater cross-product interoperability, including harmonised masks, basin definitions, grounding-zone representations, spatial reference frameworks and consistent uncertainty layers. Integration of this sort would increase the scientific value of the whole suite and improve usability for model evaluation.

Second, there is a strong case for improving guidance on product scale, limitations and appropriate use. One of the clearest messages from the literature is that the products do not all serve the same scientific role. GMB is powerful for basin and continental scale analyses, but not at the individual glacier scale. GLL is robust for major marine outlet systems, but not always sufficient for event-scale retreat or small Antarctic Peninsula glaciers. IV is excellent for recent seasonal and short-timescale dynamics, but less suitable by itself for multi-decadal continuity without merging with other products. Clearer use-case-oriented guidance would make the products easier to apply.

Third, uncertainty communication should remain a central priority. AIS_cci+ products are already relatively strong in this area, especially in comparison with many general remote-sensing datasets, but climate-assessment use requires more than technical error estimates. Users need uncertainty information that is meaningful in terms of the scientific question being asked: whether a product is reliable for trend detection, for event-scale interpretation, for model validation, or for basin-scale integration. The gravimetry literature is particularly instructive here, because it shows how strongly Antarctic conclusions can depend on processing choices and on the treatment of centre-to-centre spread across CSR, JPL and GSFC products (Pan et al., 2025; Jiao et al., 2023; Dahle et al., 2025). A similar approach could be more widely adopted across the AIS_cci+ suite of data products.

Fourth, there are several product-specific development priorities. For SEC, the main need is improved process partitioning, especially between dynamic change and firn- or snowfall-related signals, and stronger direct application over floating ice shelves. For IV, maintaining and extending the dense temporal coverage of the Sentinel-1 era is essential, and there may be value in providing lower-resolution aggregated products or derived strain/divergence layers that are easier for some modelling communities to use. For GLL, the strongest priorities are denser time series in key dynamic sectors, clearer metadata on grounding-line proxy definition, and continued development of automated delineation workflows. The option of providing more model-friendly gridded or distance-to-grounding-line products should be considered. For GMB, more explicit linkage to competitor gravimetry products and clearer guidance on effective resolution and interpretation would strengthen confidence and uptake. Figure 13 shows the user-friendly interface for hte GravIS variant of the GMB dataset developed by GFZ, which has led to increased data use.

A related recommendation concerns the relationship between AIS_cci+ and other major data providers, especially NASA MEaSUREs and ITS_LIVE for ice velocity and grounding-related products, and CSR/JPL/GSFC for gravimetry. The literature reviewed here does not support a simple “best product” narrative. Instead, the products often occupy different but overlapping niches. ESA CCI IV, for example, is particularly strong for recent monthly Antarctic margin dynamics, while MEaSUREs and ITS_LIVE remain essential for longer historical context. Likewise, the AIS_cci+ GMB product is especially useful as an Antarctic science-ready dataset, while CSR, JPL and GSFC products are often more central in methodological comparison or inversion studies (Davison et al., 2025; Pan et al., 2025). Rather than framing these as competing systems, it would be more useful to provide explicit cross-programme guidance describing their respective strengths, limitations and best-use cases. Such guidance could take the form of harmonised documentation, intercomparison tables, or a high-level synthesis paper targeted at the wider climate and cryosphere communities.

Finally, it may be useful to consider the value of higher-level climate indicators in future phases of the AIS_cci+ programme. The review carried out here suggests several particularly promising directions: dynamic discharge products that combine SEC and IV; grounding-line migration-rate products based on denser GLL time series; firn-adjusted dynamic thinning layers derived from SEC; regional or basin-based freshwater-flux indicators linked to GMB; and integrated early-warning metrics that combine grounding-line retreat, acceleration, thinning and ice-shelf weakening. These would not replace the core ECVs, but would provide added scientific value and would align well with the needs of climate assessment and model evaluation.

In summary, the AIS_cci+ project has delivered a scientifically strong and increasingly useful set of Antarctic climate products. The next stage of development should build on this success by strengthening integration across products, improving uncertainty communication by use case, increasing compatibility with complementary programmes. It may be valuable to consider developing higher-level indicators that connect observation more directly to climate risk, model evaluation and early warning of rapid change.

5.2 Outreach and communication

The AIS_cci+ project has generated a scientifically strong and increasingly policy-relevant set of Antarctic climate data records. A clear next step is to ensure that these products are not only discoverable and downloadable, but also more deeply embedded in the tools, communities and communication channels through which climate knowledge is used. The current ESA Climate Change Initiative project pages present the Antarctic Ice Sheet project as a provider of long-term and reliable climate data records from satellite observations, and the wider CCI+ programme continues to emphasise uptake by climate research and climate services communities.

One important opportunity remains stronger linkage to the Earth System Model Evaluation Tool (ESMValTool) and related model-evaluation workflows. ESMValTool has already demonstrated the value of ESA CCI datasets for model evaluation in a range of domains, including sea surface temperature, sea ice, cloud, soil moisture, land cover, aerosols, ozone and greenhouse gases. ESA CCI diagnostics are therefore already part of the established ESMValTool ecosystem, and the tool has continued to broaden its recipe base and rapid-evaluation capabilities. Extending this framework to include Antarctic ice-sheet diagnostics derived from AIS_cci+ products would be a logical and timely development, particularly as interest grows in coupled ice-sheet-climate interactions within Earth system modelling.

This is especially relevant because the modelling community served by AIS_cci+ is evolving. Ice-sheet modelling is no longer confined mainly to stand-alone ice-sheet groups; it is increasingly being incorporated into coupled climate and Earth system modelling environments. ESA's Climate Modelling User Group has already identified ice sheets as an active area of cross-ECV climate science, including the evaluation of atmospheric and surface processes affecting ice sheets and their variability in climate models. AIS_cci+ should continue to engage with this shift by ensuring that its products are visible not only to specialist glaciological modellers, but also to larger climate-modelling centres and infrastructure projects.

A second important communication priority is to strengthen cross-programme scientific outreach within ESA. The reviewed literature shows that AIS_cci+ products are particularly powerful when interpreted alongside related observations and modelling activities, for example in sea-level budget closure, Southern Ocean change, tipping-point studies and cross-ECV analyses. ESA is already supporting connected activities in this space, including projects on polar ice sheets and tipping elements. There is therefore a strong case for positioning AIS_cci+ more explicitly within a wider ESA climate-observation narrative, rather than communicating it only as a stand-alone cryosphere activity.

The project should also maintain and deepen its strong engagement with the international glaciological research community. This remains one of the programme's real strengths. Earlier sections of this review showed that AIS_cci+ products are already being used in high-profile studies of discharge, grounding-line retreat, mass balance and process understanding. Continued participation in collaborative projects, model intercomparison activities and international assessments will remain essential if the products are to retain visibility and scientific relevance. This is particularly important as Antarctic science becomes more tightly connected to sea-level assessment, Earth system modelling and climate-risk analysis.

Beyond the research community, Antarctic ice-sheet change remains one of the most visible and publicly resonant aspects of climate change. Satellite observations of grounding-line retreat, glacier acceleration, thinning ice shelves and changing mass balance provide compelling evidence of ongoing change and are highly effective in communicating why polar climate science matters. This public-facing value is not the primary purpose of the CCI programme, but it is an important secondary outcome and could be strengthened further. A practical step would be to curate a clearer library of non-technical figures, short explainers, annotated maps, animations and presentation-ready visuals that can be used by teachers, communicators, early-career researchers and policymakers. ESA's project webpages already provide an accessible starting point for this, but there is scope for a more deliberate communication package built around the AIS_cci+ products themselves.

Training and capacity-building also deserve continued emphasis. Earlier efforts across the ESA CCI programme, including online courses and broader educational resources on climate change and Earth observation, have shown the value of structured training for widening product uptake. In the current phase, the same principle applies to AIS_cci+: uptake will be strongest where users can move easily from product awareness to practical application. This argues for more short technical tutorials, example workflows, "how to use this product" notes, and worked climate- or model-evaluation case studies, especially for non-specialist users entering Antarctic research from the climate, sea-level or Earth system communities.

Finally, communication about AIS_cci+ should be more explicit about its relationship to other major observing programmes. The literature reviewed earlier shows that the AIS_cci+ products often complement rather than replace products from NASA MEaSUREs, ITS_LIVE, CSR, JPL and GSFC. Outreach material should therefore help users understand not only what AIS_cci+ provides, but also where it adds distinctive value and how it can be combined with other datasets. That kind of comparative guidance would be scientifically useful, would reduce confusion for non-specialist users, and would position ESA's Antarctic products as part of a broader international observation ecosystem rather than as isolated alternatives.

In summary, outreach and communication for AIS_cci+ should now move beyond product availability alone and focus more strongly on integration, usability and visibility. The most important priorities are:

- embedding AIS_cci+ products within model-evaluation frameworks such as ESMValTool;
- strengthening links with the evolving climate and Earth system modelling community;
- increasing cross-ECV and cross-programme visibility within ESA;
- providing more accessible non-technical communication material for public and policy audiences;
- and developing practical training resources that help new users apply the products confidently and correctly.

These steps would increase both scientific uptake and wider societal value, while ensuring that the strong technical achievements of AIS_cci+ translate more fully into climate assessment, model development and public understanding.

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