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

Greenland_Ice_Sheet_cci+ (GIS_cci+)

Climate Assessment Report (CAR)

Prime & Science Lead:	Louise Sandberg Sørensen DTU Space, Copenhagen, Denmark
Technical Officer:	Anna Maria Trofaier ESA ECSAT, Didcot, United Kingdom
Consortium:	Asiaq Greenland Survey (ASIAQ) DTU-Space, Department of Geodynamics (DTU-S) DTU-Space, Department of Microwaves and Remote Sensing (DTU-N) Danish Meteorological Institute (DMI) ENVironmental Earth Observation IT GmbH (ENVEO) Science [&] Technology AS (S&T) Technische Universität Dresden (TUDr) The Geological Survey of Denmark and Greenland (GEUS) The Niels Bohr Institute (NBI) Northumbria University (NU)

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Signatures page

Prepared by	Ruth Mottram Lead Author, DMI	Ruth Mottram Digitally signed by Ruth Mottram Date: 2025.01.13 15:45:33 +01'00'
Checked by	Louise Sørensen, Prime and Science Lead, DTU-S	Digitally signed by Louise Sandberg Sørensen Date: 2025.01.13 15:02:21 +01'00'
Issued by	Daniele Fantin, Project Manager, S&T	Digitally signed by Daniele Fantin Date: 2025.01.13 14:58:40 CET
Approved by	Anna Maria Trofaier ESA Technical Officer	

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Acronyms and Abbreviations

Acronyms	Explanation
ATBD	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CFL	Calving Front Location
CONAE	Comisión Nacional de Actividades Espaciales
CS2	CryoSat-2
CSR	Center for Space Research, University of Austin
DEM	Digital Elevation Model
(D)InSAR	(Differential) Interferometric Synthetic Aperture Radar
DL	Deep Learning
DMI	Danish Meteorological Institute
DTU-N	DTU Microwaves and Remote Sensing Group
DTU-S	DTU Geodynamics Group
E3UB	End-to-End ECV Uncertainty Budget
ECV	Essential Climate Variable
ENU	East North Up
ENVEO	ENVironmental Earth Observation IT GmbH
EO	Earth Observation
ESA	European Space Agency
GCOS	Global Climate Observation System
GCP	Ground Control Point
GEUS	Geological Survey of Denmark and Greenland
GFZ	Deutsche GeoForschungsZentrum
GIA	Glacial Isostatic Adjustment
GIS	Greenland Ice Sheet
GLL	Grounding Line Location
GMB	Gravimetry Mass Balance
GRACE(-FO)	The Gravity Recovery and Climate Experiment (Follow On)

IMBIE	Ice Sheet Mass Balance Inter-Comparison Exercise
InSAR	Interferometric Synthetic Aperture Radar
IPP	Interferometric Post-Processing
IV	Ice Velocity
JPL	NASA Jet Propulsion Laboratory
MAI	Multiple Aperture Interferometry
MEaSUREs	Making Earth System Data Records for Use in Research Environments (NASA)
MFID	Mass Flux and Ice Discharge
NBI	Niels Bohr Institute, University of Copenhagen
NEGIS	North East Greenland Ice Stream
NU	Northumbria University
OT	Offset Tracking
PROMICE	Danish Program for Monitoring of the Greenland Ice Sheet
RA	Radar Altimetry
RMS	Root Mean Square
S&T	Science and Technology AS
S2	Sentinel-2
SAR	Synthetic Aperture Radar
SEC	Surface Elevation Change
SLR	Satellite Laser Ranging
SMB	Surface Mass Balance
SOW	Statement of Work
TEC	Total Electron Content
TOA	Top of Atmosphere
TPROP	Technical Proposal
TUDr	Technische Universität Dresden
UL	University of Leeds
URD	User Requirement Document
TOPS	Terrain Observation by Progressive Scans

Executive Summary

This report serves three purposes. Firstly, we give an overview of the datasets made available in the ESA Climate Change Initiative for the Greenland ice sheet, including current and potential uses and a look at up-and-coming projects that will build on these. Secondly, we look at two case studies in detail using the data, together with other in-situ observations and climate model outputs and show how the GrIS CCI data can contribute to both international intercomparisons such as ISMIP7 in CMIP7 and to give good process insights.

The case studies aim to gain insight into the state of the mass budget of the Greenland ice sheet, how it should be partitioned between different processes, and where the data themselves can be used to evaluate climate models. The case studies build on collaborations between the ESA CCI and the Horizon 2020 project PolarRES and therefore are also a model for future collaborations between ESA and the Horizon research communities.

Finally, we present an overview of other studies, both published and up and coming and present some recommendations for improvements in future CCI projects.

1 Introduction

1.1 Purpose and Scope

This document is a new Climate Assessment Report (CAR), summarising the work carried out over the 2nd phase of the next phase of the "Greenland_Ice_Sheet_cci+" (GIS_cci+) project, in accordance with the Contract [AD1] and Statement of Work [AD2].

This CAR is, like the predecessor climate assessment reports, part of Task 5 "Assessment of ECV Products by Climate Science and Climate Service Users" within the CCI+ GIS project. The original document was based on the Phase 1 Climate Assessment Report (CAR) [RD2], of the "Ice_Sheets_cci" project.

This document includes new use cases of the Greenland ice sheet data by the scientific community including two specific case studies and some planned activities. We focus in particular on published or soon-to-be-published analysis. We also identify opportunities for further analysis of produced datasets in collaboration with climate modelling and engagement with other scientists in the ice sheet community, in the framework of international science collaborations. Outreach to the public is a relatively small part of this report, but it may be noted that it can have an outsize influence on how the aims and achievements of ESA climate change initiative is perceived and we therefore make some suggestions about accessibility.

Finally, we identify some open possibilities for further studies with the existing datasets that we encourage GIS_CCI to take up in the next phase and offer some new suggestions to make the datasets easier to work with for non-specialists in remote sensing.

We also append three papers (in draft format), that are not to be shared more widely until accepted for publication.

1.2 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	ESA/Contract No. 4000126523/19/I-NB - Greenland_Ice-Sheets_CCI+ and its Appendix 1 (incl CCN3)	CCI+ Phase 1 New R&D pm CCI ECVs for Greenland _Ice Sheet_cci (incl CCN3)	Cont: 2019.03.06 CCN3: 2022.12.05	-
AD2	ESA-EOP-SC-AMT-2021-53	Climate Change Initiative Extension (CCI+) Phase 2 - New R&D on CCI Essential Climate Variables -SoW (incl Annexes)	2022.06.10	Issue 1 Revision 2

2 Overview of GIS_CCI data products

The commitment by ESA's CCI project to provide easily accessible, standardized data sets based on the vast amount of archived Earth observation data sets facilitates research in Earth and climate science. The conversion of satellite data into finalized data products of use to the climate research community requires specific knowledge and experience and can be a time-consuming task. Individual climate research groups do not always possess the necessary experience or required resources to do this. By relaying the processing of available observations into standardized data sets to dedicated consortia, major obstacles to the utilization of existing Earth observation data by the research community have been removed.

The GIS_cci operationally produce four long-term ECVs (SEC, IV, GMB, MFID), a research-based glacial lakes product for two major outlet glaciers (SGL) as well as two older datasets that are no longer continued: GLL and CFL. For the purposes of this report, we use the following abbreviations for the different ECV datasets:

Surface Elevation Change (SEC):

5-year mean surface elevation change products cover the period 1992-present based on all available data sources. A new data product of higher temporal resolution has just been released (2010-present).

Ice Velocity (IV):

Several horizontal ice velocity data products are generated and published. These are based on RA different datasets and techniques. Some are Greenland-wide, while others (due to data limitations) cover specific glaciers. A new product has been released on the line of sight displacement, useful for studying e.g. subglacial water transport.

Gravimetric Mass Balance (GMB):

The ice sheet mass changes are available for the GRACE/FO period (2002-present) at monthly resolution. There is a data gap between the GRACE and GRACE-FO missions. The mass changes are available for the entire ice sheet and at the drainage basin scale.

Mass Flow Rate Ice Discharge (MFID):

The solid ice discharge provides mass fluxes for all outlet glaciers of the Greenland Ice sheet as a monthly resolution since 2015.

Supraglacial Lakes (SGL):
The SGL product generated covers selected regions and years. The product contains lake outlines and depths.

From an observational point of view, these data sets offer a direct quantitative measure of ice sheet change, necessary evidence to establish observational baselines and capture the evolution of the ice sheets within the global climate system. A time series of ECVs from all available data back in time in a common format provides the climate research community with tools to assess ice sheet mass loss and the important processes that drive this.

3. Climate Research Activities in GrIS CCI

3.1 Research and Dissemination Activities

The CCI+ GIS CRG has raised awareness of and introduced the use of GrIS CCI in several new activities, including boot camps, joint workshops with Horizon 2020 and Horizon Europe projects, participation in the EU Polar Science Week and several Greenland-focused climate conferences. We have found that these in-person or hybrid events can be a very successful forum - not only in promoting the existence of the CCI GIS datasets but also in promoting their use. In particular, a series of boot camps in collaboration with various different projects and organisations (see below) held in Denmark in 2022, 2023 and 202 have promoted the use of CCI GIS and other CCI datasets with climate model outputs and in-situ observations (e.g. MOSAiC).

3.1.1 Collaborative Workshops with Horizon Europe and Horizon 2020

The GrIS CCI consortium, including CRG members, was invited to two different workshops held in Copenhagen in 2022 and 2023. The aim of these workshops was to promote closer links between modelling and observational communities and to assess how CCI GIS and other CCI datasets could be applied together with climate model outputs for evaluation and impact studies. The first workshop in 2022 was organised within the Horizon 2020 project PolarRES and was reported on in a deliverable report available on Zenodo. Also represented were IMBIE, 4DGreenland and the CCI projects for sea ice, land surface temperature and Antarctica as PolarRES is a bipolar project. Participation in this workshop led directly to invitations to participate in the PolarRES and NORP bootcamps and to the case study presented in this report.

Other collaborations have been promoted by the CRG representation at the Nuuk Climate and UN Ocean Decade conference in October 2024 and at European Polar Science Week in September 2024.

3.1.2 Early Career Researcher (ECR) Bootcamps

The initiation of an ECR bootcamp was originally led by CliC/CLIVAR Northern Oceans Regional Panel (NORP) where Ruth Mottram at DMI took a leading role in the organisation of the bootcamp itself. Funding was obtained from a range of different sources, including a contribution from the CRG budget for GrIS CCI. Mentors and teachers at the bootcamp were both NORP members and invited scientists from a range of institutes, including CCI GIS and Sea Ice CCI. The theme of the first was the characterization of Arctic processes in CMIP6 models where CCI data was presented as an evaluation tool as well as a potential process development tool together with outputs from the CARRA (Copernicus Arctic Regional Reanalysis) data. Four papers have been published since the boot camp in October 2022, all of which were initiated there. None of these yet include GrIS CCI data directly, but the results show the potential of boot camps to help push research in a given direction. Two subsequent boot camps were organised by the Horizon 2020 project PolarRES specifically as a follow-on and a third is planned for 2025, with funding from a range of different projects. At both these bootcamps GrIS CCI data was presented and a project was initiated, in the context of an ESA CMUG project to use these data with outputs from regional climate models from the PolarRES project. This project is the basis of the case study presented below.

The boot camp format focuses very much on project work, with a few lectures on specific technical topics and some broader generalist skills, in contrast to a summer school where the focus is much more on teaching and learning. They are similar to hackathons in bringing together scientists with different skills and specialisms, but hackathons often focus on code development and short-term project aims. With the bootcamp series we have worked on multiple, often related scientific problems and see them as an accelerated start of a specific scientific project. The role of senior scientist mentors was key in many of the most successful projects, not only in helping to develop ideas, but also to ensure that the ECRs actually working on the science and the publications were able to keep contributing after the bootcamp was over and to bring the publications through the whole process. The bootcamps are also a relatively cheap means to bring together PhD students, post-docs and in some cases MSc students from many different countries and as such are also very good networking opportunities. Indeed, part of the motivation behind the first was that in a COVID world, there was a PhD generation who had not had the opportunity to mix with each other which was typical for early career researchers.

The GrIS CCI data is particularly suitable in this context because it has already been processed, and homogenised (to some extent) and is generally well described. The datasets are thus, if not quite plug and play, relatively easy to handle, whereas many remote sensing data require additional processing. We suggest that other CCI projects and spin-offs could start to explore bootcamps, hackathons and similar as part of promoting outreach and use of CCI datasets more widely.

3.2 Initiated projects with applications of GIS CCI datasets

The established nature of the GrIS CCI means that several high-impact research projects can now use the CCI+ GIS products: ARCFRESH, PISCO, ICELINK, CMUG, Digital Twin.

ARCFRESH: This is one of the X-ECV projects initiated by ESA in 2024. The overall objective of ARCFRESH is to advance the current state of knowledge on freshwater fluxes and freshwater budget in the Arctic Ocean, maximizing the use of Earth Observation (EO)-derived ECV datasets generated in the CCI program. Specifically, this project will rely on the MFID, IV, GMB and SEC datasets of CCI+ GIS together with regional climate models to assess the amount of freshwater transported from the Greenland Ice sheet to the Arctic Ocean.

ICELINK: Advancing Knowledge of North Atlantic Land ICE - LINKing Observations and Models (ICELINK) is a recently-funded Horizon Europe project that will bridge the knowledge gap between climate models, ice-flow models, satellite observations and in-situ observations to accelerate the understanding of how glaciers and ice sheets in the North Atlantic respond to climate change, and their impacts on climate and ecosystems. An improved understanding of trends and variability of ice evolution is important, and ICELINK will address this challenge by integrating Earth Observation data, in-situ observations and ice flow and climate models into an improved understanding of the processes that control the evolution of glaciers. The project is led by Christine Hvidberg and the consortium includes several CCI GIS partners.

Digital twin Ice sheets: A data-driven digital twin for ice sheets is a sophisticated virtual representation of Earth's cryosphere, built on observational and simulation data. It serves as a predictive and analytical tool to study ice sheet dynamics and their global impacts. Within the EO-driven Digital Twin for Ice Sheets, we have four use cases, to enable stakeholders to evaluate “What-if” scenarios. The four use cases are as follows: (1) Hydropower: Ice sheets influence freshwater availability, and river systems are fed by glacial melt. The digital twin can help model how changing ice dynamics affect water resources, which is crucial for hydropower projects. By forecasting meltwater flow and volume, stakeholders can optimize energy production and infrastructure planning. (2) European Sea Level Fingerprint: The melting of ice sheets contributes to sea level rise, but the distribution is not uniform due to gravitational and Earth deformation effects, known as "sea level fingerprints." The digital twin can provide precise, localized projections of sea level changes, which are critical for Europe’s coastal regions and align with environmental risk mitigation strategies. (3) Ice Shelf State and Fate: Ice shelves act as buffers that slow the flow of continental ice into the ocean. Monitoring their stability and modelling their future behaviour is vital for understanding long-term sea level rise. (4) Enhanced Surface Climate: Ice sheets significantly influence regional and global climate systems, including surface temperature, precipitation, and wind patterns. By integrating data from the digital twin, we can refine climate models and improve predictions. Together, the latter three use cases build on research and development from the CCI.

PISCO (Polar Ice Sheets in Climate Models and Earth Observation) is an ESA-funded 2-year project, still currently at the negotiation stage (and so not yet confirmed), that will use climate model outputs together with CCI ECVs, including data from both GIS-CCI and AIS-CCI to assess better the processes that affect polar ice sheet mass budget. Building on a CMUG project (WP5.2) and using the latest generation of regional climate models for the polar regions, produced in the

Horizon 2020 project PolarRES, PISCO will focus on process understanding. In particular, PISCO plans to use GMB, SEC, CFL and IV data as part of the planned analyses in the project.

3.3 Contributions to IPCC and other international organisations

The high quality and consistent datasets of Greenland ice sheet processes assembled in the GrIS CCI mean that the GrIS CCI has an important role to play in contributing to the IPCC (Intergovernmental Panel on Climate Change) assessments, in particular via the IMBIE (Ice Sheet mass budget intercomparison exercise). GrIS CCI has been featured in all IMBIE reports (e.g. Otosaka et al., 2022; Shepherd et al, 2020), particularly the GMB and SEC datasets. However, process insights based on analysis of the datasets can be extended and that is the focus of the case studies featured below. A new update to the IMBIE project, again featuring input from GrIS CCI will shortly be submitted to ESSD (Otosaka et al., 2025) and this will again be a highly impactful publication of the GrIS CCI research. The latest IMBIE update confirms previous IMBIE assessments with a continuing loss of the Greenland ice sheet. Broadly speaking, the uncertainties in Greenland mass loss are much smaller than those in Antarctica, with different methods (input-output assessments, Gravitational methods) agreeing well within error estimates. Nonetheless, Otosaka et al. (2025) note that there remain some compensating biases between methods which affect efforts to partition mass loss processes. Clarifying these different biases will require ongoing work, and extra urgency is added by e.g. a recent study (Glaude et al., 2024) showing that small differences in present-day SMB estimates can sum up to large differences in future estimates of ice sheet change. In this sense, GrIS CCI data has a crucial role to play.

Beyond IMBIE, there is potential for GrIS CCI to make a contribution to IPCC work via the CMIP (Coupled Model Intercomparison Project). In preparing for the next (7th) assessment report for the IPCC, CMIP7 will run a new round of sensitivity experiments and projections. While the final timetable is yet to be finalised, many modelling groups are preparing already for the core DECK experiments as well as the many model intercomparison projects around it. Relevant to the GrIS CCI is the ISMIP7 group (Ice sheet model intercomparison project, https://github.com/ismip), which will include both ice sheet dynamics modelling, coupled climate and ice sheet models and a surface mass budget model sub-group. A meeting is currently planned for Copenhagen in 2025 (subject to funding application) in which GrIS CCI will be engaged to participate with the intention of incorporating data into an OBS4MIP (Gleckler et al., 2024) style framework if possible. A potential example of how this can work is shown in the case study below.

3.3.1 Case Study: Use of IV to assess ice sheet model outputs for use in the ISMIP7

The PISM (Parallel Ice Sheet Model) dynamical ice sheet model is run at multiple institutes globally as a flexible ice sheet dynamics model, primarily in Greenland, but also in Antarctica. At DMI the PISM model is run both offline and online, as part of the fully coupled earth system model (ESM), EC-Earth3 (Madsen et al., 2022). The model has been included in a set-up that conforms to CMIP6 and CMIP7 specifications. In this case study we show how the GrIS CCI data can be applied as an evaluation of an ISMIP/CMIP7 ice sheet model.

In order to determine the ice sheet's response to climate change, the ice sheet itself needs to be initialised such that it has a realistic extent, thickness, velocity and temperature profile when compared with the real world ice sheet (e.g. Nowicki et al., 2016). This is typically done using a model and repeatedly running it for millennia with a simple forcing. In the case of EC-EARTH - PISM, and other fully coupled ESMs with ice sheet models, this is done offline (that is not dynamically coupled into the ESM). The ice sheet model is run into an equilibrium state before it is coupled to the Earth system model, or in the case of ice sheet models run offline, as the majority were in ISMIP6 (Goelzer et al., 2020), before experiments with different climate forcing are applied. The full EC-EARTH-PISM ESM is run together such that the atmospheric and ocean forcing is applied to the ice sheet on a monthly basis and then fluxes and topographic changes from the ice sheet are put back into the model (Madsen et al., 2022).

As we do not have perfect knowledge of the past few glacial cycles, during which the ice sheet built up, we need to make some assumptions when spinning up the ice sheet to present-day conditions. For example, with long simulations of PISM the offline model is typically run using a forcing based on modern climate but corrected for long-term climate cycles with ice core data on temperature and precipitation changes over the last ~130,000 years. CCI IV data is an obvious evaluation dataset for these different spin-ups as it allows us to compare modelled IV with observed. Figure 1 below shows one example of a comparison between an offline PISM simulation, used to spin up to present-day ice velocity and a comparison with the CCI IV data and with the NASA Measures velocity dataset for completeness.

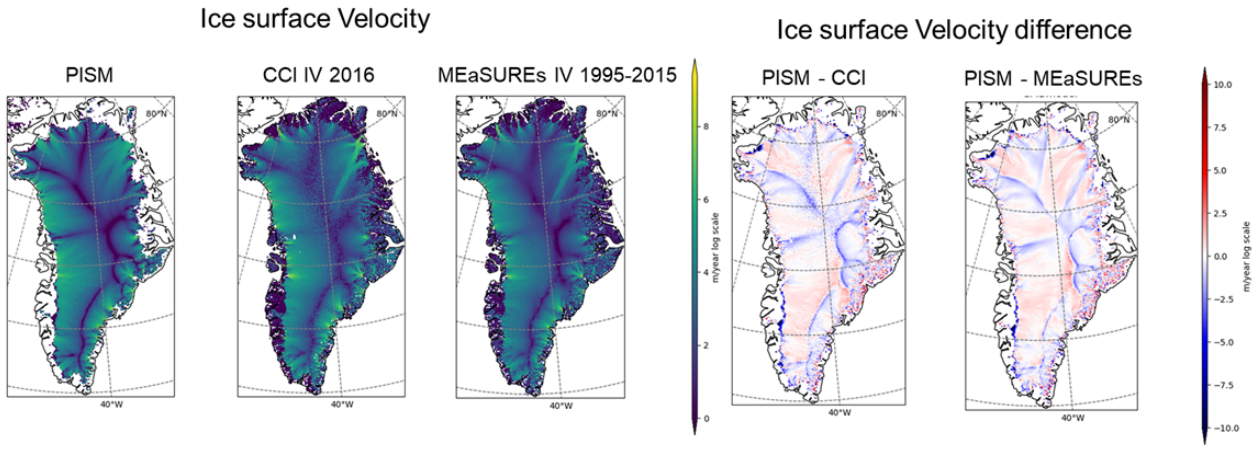

Figure 1. Ice surface velocity (annual mean) from the PISM ice sheet mode and compared with two IV datasets from the CCI and the MEaSUREs IV data. The two anomaly plots on the left show how the model differs compared to the observations. (Plots by Chenhi Di, University of Copenhagen/DMI)

The maps in Figure 1 show the modelled and observed IV - note that the three absolute IV plots are shown on a log scale to highlight that slow-moving ice divides in blue and the faster-moving ice streams in yellow. The PISM model does a fair job at representing the IV of Greenland but, likely due to the lower resolution of the model and perhaps differences in parameterisations and some missing processes, some ice streams appear to be too wide and/or not fast enough in the model. The anomaly plots on the right show more clearly that some of the ice divides are not in quite the right location, and the edge of the ice sheet appears poorly resolved, particularly in western Greenland.

Overall, this case study demonstrates that GrIS CCI will be a valuable addition for assessing and evaluating modelled GrIS dynamics and we encourage the adoption of this and other GrIS CCI datasets by the ISMIP7 working group. Other datasets, such as for example MFID, GMB and CF may also be useful in this context for assessing how well ice sheet models can represent observed changes in GrIS. An example of how this could look is shown below (from Aschwanden et al., 2021). Aschwanden et al (2021) used IMBIE results, but a similar analysis would be fairly easily applied to other ECVs produced by the GrIS CCI.

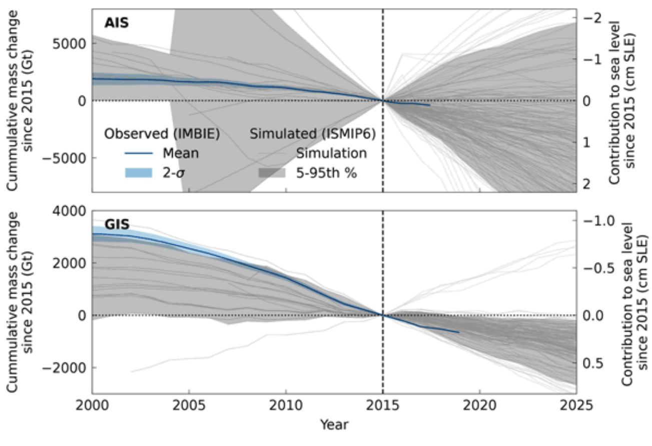

Figure 2. Observed and simulated historical mass changes from the Antarctic ice sheet (AIS) and Greenland ice sheet (GIS) between 2000 and 2020 in gigatons (Gt) and centimeters of sea level equivalent (cm SLE). A consensus estimate of observed mass changes (The IMBIE team, 2018; The IMBIE Team, 2019) is plotted in blue along with their

respective uncertainties (shaded). The ensembles of ISMIP6 (Goelzer et al., 2020; Seroussi et al., 2020) historical simulations and projections are plotted with dark-gray lines, and the 5th to 95th percentile mass loss rates are shown as a 90 % credibility interval with light-gray shading. Due to the large variance in ISMIP6 historical simulations for Antarctica, the uncertainties in IMBIE are not visible in the plot. Taken from Aschwanden et al., 2021.

4 Scientific Case Studies

4.1 Case study: Using GrIS CCI to evaluate Climate Models

A new ensemble of regional climate models (RCMs) is now available via the Horizon 2020-funded project PolarRES. The outputs from these models are in the process of being uploaded to the open ESGF (Earth System Grid Federation) dataservers as part of the WCRP CORDEX (World Climate Research Programme, Co-Ordinated Regional Downscaling EXperiment) project but as collaborators in the project, we took the opportunity to test if the outputs from the models can be used with GIS CCI data, both SEC, for model evaluation but also IV, MFID and GMB (see following case study).

Model	Grid Type	Nudging Type	Grid points (X and Y)	Resolution
HCLIM Arctic	Polar Stereographic	Spectral	640 × 720	11 km
HCLIM Antarctic	Polar Stereographic	Spectral	750 × 648	11 km
RACMO Arctic	rotated latitude-longitude	grid-point	646 × 650[a]	11 km
RACMO Antarctic	rotated latitude-longitude	grid-point	726 × 591[a]	11 km
MAR Antarctic	Polar Stereographic	grid-point	610 × 544	12.5 km
MAR Arctic	Polar Stereographic	grid-point	540 × 560	12.5 km
MetUM Arctic	rotated latitude-longitude	Re-initialised	612 × 608	11 km
MetUM Antarctic	rotated latitude-longitude	Re-initialised	560 × 688	11 km
ICON Arctic	unstructured triangular	grid-point	356 × 320	11.3 km
WRF Arctic	Polar Stereographic	grid-point	600 × 573	11 km

Table 1. Table showing atmospheric model set-up used by different groups for these experiments. [a]Including boundary relaxation zone.

Table 1: List of models and their set-up developed in PolarRES, the output of which is used in this case study. This is Table 1 in the paper (Mottram et al., in prep.) describing the experimental protocol of the PolarRES RCM simulations.

In this case study, we compare the CCI SEC data with an equivalent, the precipitation minus the evaporation and sublimation variables of the RCMs. Ice sheet elevation change is the result of two different processes, the surface mass budget (SMB) and the ice sheet dynamics. As SMB is measured at only a few points on the ice sheet, RCMs are generally used to produce estimates of SMB used for total mass budget estimates. However, it is difficult to assess how much snow falls and accumulates on the ice sheets, especially because in-situ measurements are unreliable. In this case study, we therefore use the SEC dataset as an independent form of evaluation of the modelled accumulation in the new PolarRES ensemble of RCMs. In the following case study we examine some of the implications for the ice sheet mass budget by applying different CCI ECVs.

4.1.1 Methods

The RCMs were developed and run at a range of European climate research institutes that have shared the data used in this report. The details of the model set-up are given in the experimental protocol currently in preparation for publication (and shortly to be submitted), for Geoscientific Model Development (PolarRES consortium, Mottram et al.). Outputs from the models used were the precipitation, evaporation and sublimation variables, along with details of grids and topographies. All models were forced with the ERA-5 reanalysis on the boundaries, and with nudging (spectral or grid-point) or with re-initialisation within the domain to force the models to be close to the driving climatology. This allows us to make a direct time series comparison with the CCI data, rather than being confined to a climatological comparison. All the RCMs have a fixed ice mask and surface topography, and we therefore, in the following analysis have to assume that ice dynamics processes are negligible. Similarly, we do not account for snowpack processes such as compaction, refreezing and densification as not all models have these processes included. Consultation with the CCI group reveals that in any case, the SEC signal likely includes some penetration into the snowpack and probably therefore also may render these processes negligible.

To compare the SEC, with the modelled height change, all the different RCM output data sets and the SEC data were remapped onto the HCLIM grid. Developing the remapping method led to a spin-off paper attached in the appendices, as well as code to be shared via Zenodo and Github upon publication, to assist other groups in future who need to use RCM outputs with EO data. As the SEC data is given in 5-year means, we resampled the RCM output (1 hourly) to this temporal resolution to compute the anomalies for the mean of the whole period as well as the individual 5-year means. In addition, we detrended the anomalies for each of the 5-year mean periods to assess if climate variability and weather extremes can explain some of the anomalies.

As not all RCMs have full ice sheet surface models we also excluded the regions below 2000m elevation where the highest melt and runoff occurs at the present day as an ablation mask. This also filters out many of the high-slope part of the ice sheet where SEC EO data may have precision problems.

4.1.2 Results and Discussion

At the time of writing, we have access to results from the polarRES models ICON, MAR, WRF and HCLIM, with CARRA (the Copernicus Arctic Reanalysis, a new high-resolution reanalysis) and the old DMI model HIRHAM5 as supplements.

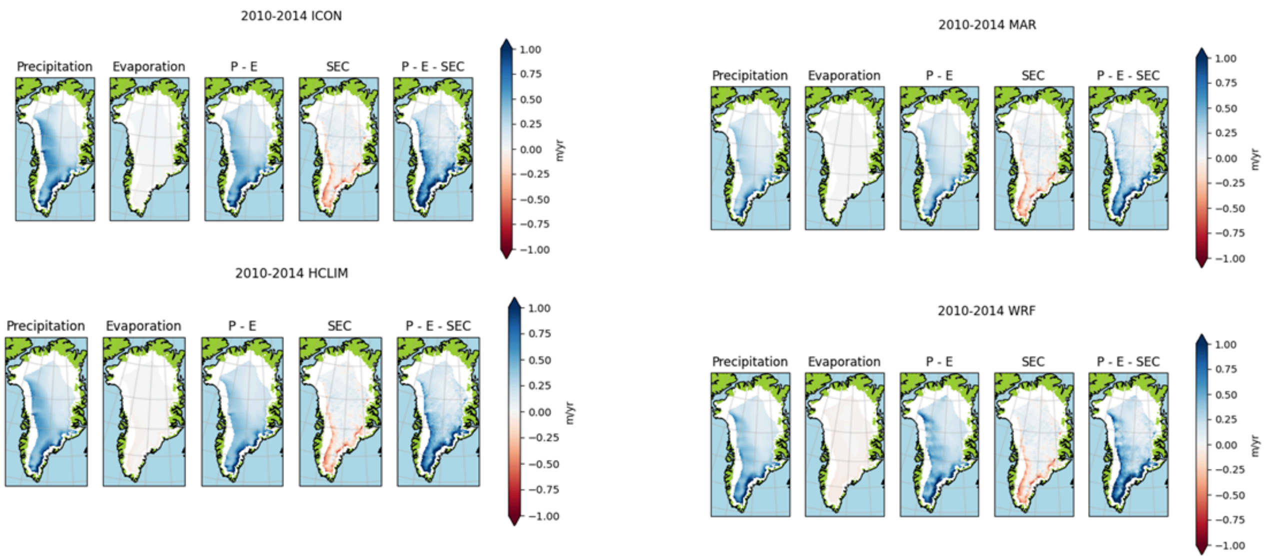

Figure 3. SEC compared with four different RCMs (ICON, MAR, WRF and HCLIM, clockwise from top left) for the period 2010 to 2014 in each sub-figure we see (left to right) mean annual precipitation (P), evaporation and sublimation (E) combined, the sum of the two, the comparable SEC data and the anomaly between observed SEC and computed P-E (P-E-SEC). Units are metres year^{-1} averaged over the 5-year SEC period. Land is shown in green, white is the ice sheet masked below 2000m elevation, blue colours indicate increased height, and red indicates reduced height. In the final rightmost pane, therefore, blue colours indicate the model overestimates height and red colours indicate the model underestimates height changes.

The analysis shown in Figure 3 indicates that the models broadly represent the pattern of SEC with close fits in the centre of the ice sheet in particular. On the ice sheet slopes, the models generally show high rates of surface elevation increase from P-E, whereas the SEC data shows a decrease in elevation. This is of course due to the lack of snow ablation and runoff in the models in this part of the analysis. The effect is also visible higher up on the south dome in the southern part of Greenland where the red colours indicate a lowering surface not captured in the P-E-only analysis which suggests that high rates of melt-driven compaction and perhaps also ablation are occurring above 2000m. ICON and HCLIM show very similar results, with WRF being slightly drier and having lower SEC. The WRF model shows some uneven patterns in the P-E data that suggest an older topographic dataset was used to define the ice sheet topography. As precipitation is very sensitive to elevation and relief, this appears to have introduced some artefacts, although overall the pattern of P-E and SEC anomaly is rather similar to the other models.

Figure 4 below shows the same data for all four periods of overlapping data but detrended by subtracting the mean SEC of all periods from each 5-year period of SEC data. The same detrending was carried out for all the models, but for simplicity we show a single example of the HCLIM RCM output here.

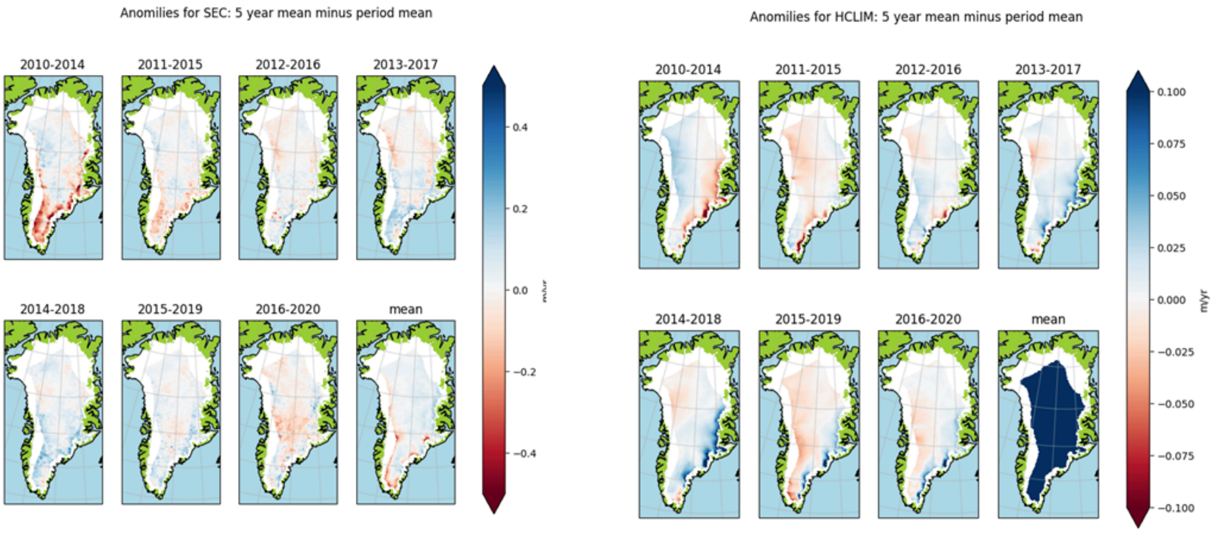

Figure 4. Detrended SEC data (left) and P-E (right) from the HCLIM model. The blue colours indicate a five year period with higher than usual accumulation and red colours show regions with lower than average.

There are some interesting patterns that jump out in Figure 4, for example, in the 2010 - 2014, period, and to a slightly lesser extent 2011 to 2015, which includes a series of high melt years (2010, 2011 and 2012), both model and SEC data show the highest reduction in elevation (thinning) of any of the period, but it appears that the model does not quite capture the same pattern, probably because the HCLIM version used here does not include surface mass budget processes such as ablation. The striking blue pattern in eastern Greenland in 2014 to 2018 and 2015 to 2019, is especially picked out in HCLIM. It may well be a record of an extreme snowfall in spring 2018 which has severe ecosystem impacts, but the SEC data does not display quite such an extreme signal, possibly, again, because of densification processes in the snowpack and perhaps also ablation of the snowfall.

Following analysis of these early results (documented in full in a paper in preparation), it is clear that, although the RCMs pattern of P-E is rather similar to that of the SEC data, some of the rather simple assumptions in this analysis can also explain some of the discrepancies. The two main assumptions are that firstly ice dynamics signal of SEC can be ignored and secondly that snowpack processes, including surface melt, refreezing and runoff are also less important for explaining SEC in the interior. We test the latter assumption with a model that includes an SMB model internally, namely the MAR model as well as the simulated SMB from an offline model driven by atmospheric output data from the CARRA reanalysis and a simpler approximation of SMB from the WRF model. We assume that the SMB can be converted to SEC using a single density value of 850 kg m-3, which may also be an important source of bias locally but appears to be a good approximation over most of the ice sheet, however, Simonsen et al., (2021) suggest a calibrated spatio-temporal correction may be used. Future work will apply this correction fully.

The results are shown in Figure 5. The models include melt and runoff but even so appear to underestimate the amount of ablation in the marginal zone, particularly in WRF in northern Greenland. The MAR model compares best with the SEC data, whereas CARRA shows a narrower ablation zone. In the interior, all the models appear to show higher mass gain than the SEC data, the more uneven pattern in WRF data is again caused by the topography dataset used in the model simulations. The SEC data also includes large bulls-eye features that are related to ice dynamics of fast-moving ice streams that draw down ice around them.

The finding that even models that include quite sophisticated snow pack schemes show increased elevation in central Greenland that is not seen in the SEC data itself suggests that some other process is counteracting the mass gain from accumulating snowfall that should lead to increased surface elevation. In this case, it is most likely that ice dynamics that seek to keep the ice sheet in a stable configuration lead to a reduction in height that is enough to counteract the increase that would be expected on a fixed topography as the models assume. Future work will use both the GrIS CCI IV dataset and modelled ice velocities (see above in Figure 1) to calculate an ice dynamics correction factor.

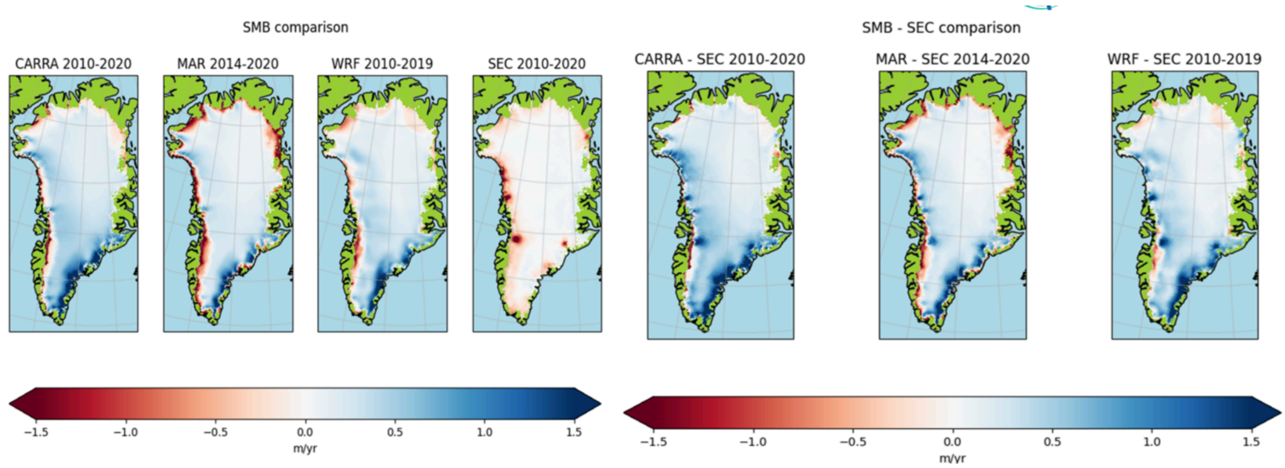

Figure 5. SMB from three different models, (from left) MAR, CARRA and WRF compared with SEC data (middle) and the anomalies of the models compared with SEC shown on the right panel three panels.

This work is still at an early stage but our results are sufficient to show that the GrIS CCI data can be used to not only evaluate climate models but also to draw out new results that give insights into interesting ice sheet processes.

4.2 Case study: ice sheet mass budget in Greenland

The outputs from these new state-of-the-art upgraded RCMs will be able to contribute to a new and hopefully improved mass budget estimate together with the MFID product for Greenland. It should also allow us to redo the analysis of Fettweis et al. (2020) to determine if there have been improvements in the SMB compared to the GMB datasets.

This work is still at an early stage as the delivery of model outputs was delayed, but we intend to recreate the figures below in Figure 6. This assessment not only delivers important details on the mass budget of the ice sheet at a higher resolution, it also acts as a model evaluation and calibration exercise, to pinpoint where models have biases, how different they are from each other and how to assess where biases may be coming from.

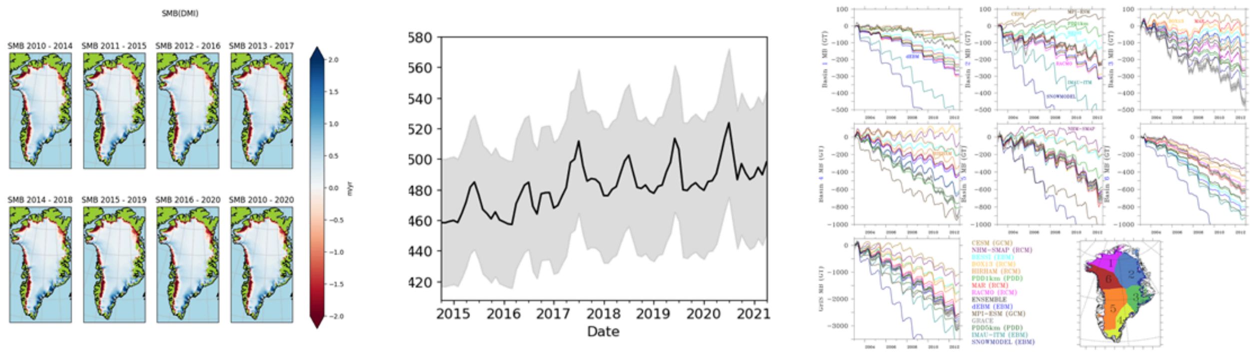

Figure 6 The use of new RCM outputs to calculate surface mass balance (e.g. left from DMI's old HIRHAM RCM) can be included together with the discharge datasets to produce MFID (centre). In Fettweis et al., 2020, SMB for a range of different models was used with discharge estimates on a basin scale and compared with the GMB data.

Figure 6 shows some experimental results, comparing SMB from the MAR model with MFID and GMB data. The numbers in Figure 7 below correspond to the regions of Fettweis et al. (2020) in Figure 6 above. GMB is compared with the total mass budget (TMB) from the MAR model, calculated as TMB = SMB-discharge. Discharge is obtained from the CCI dataset MFID, and is given on a basin scale. The MFID data used Mouginot and Rignot basins, whereas the other CCI data used for this comparison, the GMB/GRACE data is on a basin scale from Hardy et al. (2000). The discharge Fettweis et al. (2020) rely on a third definition of basins.

Unfortunately, SMB for all the models in PolarRES is not available at the time of writing. Some of the SMB data from MAR was also missing, hence the short period of comparison. The goal is to make a comparison between GMB data and the SMB-discharge, from 2002-2020 (or as many years as possible) for MAR, HCLIM, WRF, ICON, RACMO, MetUM models. Future work in the form of a CMUG project will extend to looking at GCM-based SMB and also include Antarctica. The current analysis will be written up in a scientific publication still in preparation that we aim to submit by summer 2025 (see details in the publications section below).

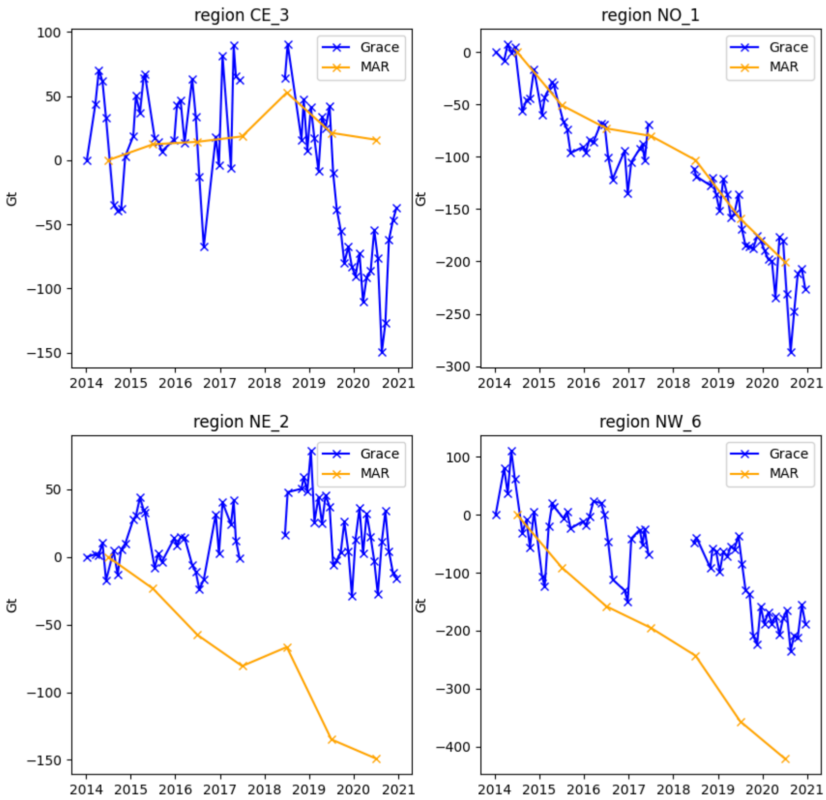

Figure 7. Comparison between MAR modelled SMB - Discharge (Mankoff et al., 2022) and GMB dataset for four basins in Greenland. Note that this is work in progress and final results may change.

4.3 Challenges in handling CCI data

In the course of these case studies we have identified several notable problems that could be eased in future iterations of the GrIS CCI.

Data Gaps: some ECVs contain data gaps, given as NaNs in files, these are complex to handle and either guidance on how to interpret these, or an interpolated data product would make working with this data easier.

Grids and Basins: It would greatly improve the user experience if it were decided to use the same definition of basins for all datasets and, for example in the context of IMBIE. The 4 northernmost basins are assumed to be the same across the different definitions, and that is how the comparison is made in Figure 7.

Guidance on common data applications: the helpful collaboration of GrIS CCI partners is essential in interpreting and using the published ECVs, but some common analyses and corrections are probably carried out multiple times by users. We expect that some guidance, e.g. how to perform firn corrections on SEC data, ice dynamics corrections and probably others could be expedited with more instruction on the website. This is partly the rationale behind the Cherblanc et al (in prep.) paper, to assist other scientists and ensure common techniques are used.

Timely Updates: while we note the idea behind the CCI is to provide climate data records, rather than operational datasets, more timely updates would be helpful for investigating particular climate and weather extremes as well as for process studies. As an example it was hoped to use the IV dataset for a project examining ice melange and calving interactions in NW Greenland, however, the data was not available for the relevant period of field observations and finally the PROMICE IV dataset was applied, along with ITSLIVE data.

5 Published Outputs

The work presented in the two case studies in this report is currently in preparation for publication with an intended submission date of mid-2025, a very early draft is available for review. There are 2 additional papers, one in revision and one about to be submitted that are given in draft form in the appendix. These cover two spin-off papers that have resulted from our analysis of GrIS CCI datasets. The first is the previously mentioned article documenting ways of working with Earth observation and RCM data (Cherblanc et al., in prep.), the second is an interesting comment piece in revision (not yet accepted) for Nature Geoscience, The Greenlandification of Antarctica, pointing out the parallels between Greenland and Antarctic ice sheets and suggesting how these similarities and differences can help to focus scientific work. This final paper builds very much on both GrIS and AIS CCI as well as the Sea Ice and Land surface temperature CCI datasets.

As these papers are not yet submitted, we have opted not to include them as appendices here but will submit them for review as separate documents.

Other publications that use CCI data:

Since the start of this phase of the project in 2023, the following papers have been published that acknowledge the use of CCI Greenland ice sheet data. These are all from outside the consortium (whose papers are listed in the full report) and show an interesting range of process studies focused on ice sheet basal processes and surface.

Blard, P. H., Protin, M., Tison, J. L., Fripiat, F., Dahl-Jensen, D., Steffensen, J. P., Mahaney, W. C., Bierman, P. R., Christ, A. J., Corbett, L. B., Debaille, V., Rigaudier, T., & Claeys, P. (2023). Basal debris of the NEEM ice core, Greenland: A window into sub-ice-sheet geology, basal ice processes and ice-sheet oscillations. *Journal of Glaciology, 268*(11), 1-10. https://doi.org/10.1017/jog.2022.122

Winton, O. A., Simonsen, S. B., Solgaard, A. M., McNabb, R., & Karlsson, N. B. (2022). Basal stress controls ice-flow variability during a surge cycle of Hagen Bræ, Greenland. *Journal of Glaciology, 68*(269), 503-517. https://doi.org/10.1017/jog.2021.111

Lu, X., Jiang, L., Xiao, C., & Li, D. (2022). Analyzing spatial-temporal variability of ice motion in Northeast Greenland from 1985 to 2018. *Frontiers in Earth Science, 10*, 972291. https://doi.org/10.3389/feart.2022.972291

Furlotti, A. (2024). 3D-Modelling of Ice Dynamics at C.H. Ostenfeld Glacier, Northern Greenland. *Unpublished manuscript*.

Mansour, I., Fischer, G., Hänsch, R., Hajnsek, I., & Papathanassiou, K. (n.d.). Correction of the penetration bias for InSAR DEM via synergetic AI-physical modeling: A Greenland case study. *Unpublished manuscript*.

6 Conclusions

In summary, we show in this report that the GrIS CCI ECVs can be used as an evaluation source for numerical regional climate and ice sheet models using SEC, IV, GMB and discharge datasets. In the course of this work, we made some interesting findings on ice sheet processes, including e.g. that the ice dynamical signal must already now be taken into account when assessing SEC from atmospheric models. The combination of models and EO data is particularly powerful when assessing ice sheet mass budget but also for insights into important ice sheet processes. Lessons from Greenland will likely become even more important as input to assessing Antarctic changes in future.

We also demonstrated a useful role for GrIS CCI data in CMIP7/ISMIP7 and the IPCC. We suggest that the ECVs can be used not only in the context of IMBIE, but also as evaluation tools for models, to assist in initialisation and to help interpret ensemble spread in the light of climate model uncertainties. Given the importance of the ice sheets and their contribution to sea level rise, the continuation of the GrIS CCI climate data record should be a priority. New scientific projects starting up in the next few months that will rely on GrIS CCI data are also a testament to the high-quality, stable climate record datasets produced within GrIS CCI and demonstrate that the project has significant ongoing scientific benefits.

Our analysis allowed us to identify some opportunities in the scientific exploitation of these results, not only in terms of improving the datasets but also for example in the production of a new SMB dataset, using the many RCM simulations now available to determine not just the “best” SMB for use with EO data but also to estimate the uncertainty range in SMB better. Another opportunity is to use GrIS CCI data together with AIS CCI data to understand better where the scientific focus on both ice sheets should be in the coming decades. These will also give an opportunity to develop outreach materials to enhance the visibility of the project’s outputs and hopefully to improve both the use of the datasets and to assist public outreach.

In spite of some identified issues such as inconsistent data grids, basin divisions and metadata attributes we find the GrIS CCI datasets to be overall well-organised, and relatively easy to use, especially in collaboration with CCI partners. The rapid changes in Greenland that are identified in this report and in the scientific literature furthermore suggest that observing areas of mass imbalance and retreat, particularly outlet glaciers, should continue to be a high priority in future GrIS CCI projects. In addition, given not only the rapid increase in ice sheet loss, but also the high pace of developments in ice sheet science, it is likely there will continue to be a high demand for CCI products. New products that could be considered include ice velocity change, grounding line migration and changes in ice dynamics, which can easily be applied to e.g. the case studies reported here.

A further opportunity for future developments is in the higher temporal resolution. This is particularly useful for surface processes, such as lake hydrology and melt but also for grounding line and ice dynamical processes. The RCM community are also interested in albedo over ice sheets as a new ECV.

To conclude, this report is enthusiastic about the possibilities offered by GrIS CCI datasets and has offered some potential suggestions for both further improvement of datasets and for the application of these datasets to help resolve long-standing and important scientific problems.

Appendix: Publications in Preparation and Published

We attach the following publications in preparation or revision that we hope will soon be accepted and that will report in the scientific literature some of the findings in this report. The appendices are included separately as they are currently not yet ready for publication.

Titles and authors:

1. The Greenlandification of Antarctica. In revision for Nature Geosciences
2. Transforming polar climate model output for data analysis using CDO and Python, in prep. for GMD.
3. Novel combinations of satellite and regional climate model outputs to assess ice sheet mass change in the 21st century.
4. Where does the glacier end? The role of landfast ice and melange in suppressing calving at outlet glaciers, In prep. for the Cryosphere.

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