ESA Climate Change Initiative (CCI)

Greenland Ice Sheet (GIS) Essential Climate Variable (ECV)

Climate Assessment Report (CAR)

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Signatures page

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Change Log

Issue	Author	Affected Section	Reason	Status
1.0	S.H. Svendsen	All	First issue for Y1 in Phase 2	
1.1	Rene Forsberg	All	Minor edits and GMB input	Released to ESA 2016-06-21
2.0	Ruth Mottram	All	Updated report to cover year 2 in Phase 2	Released to 2017-07-08
3.0	Ruth Mottram	All	Minor edits in most sections, some updates to demonstrate new science applications	Released to ESA 2018-09-17
3.1	Ruth Mottram	2.1 2.2	Updated according to ESA review: Edited incomplete sentence end of section Updated figure 2.4 on data product traffic per Q3 2018	Released to ESA 2018-10-26
4.0	Ruth Mottram	All	Complete revision to reflect recent scientific results	

Acronyms

Acronym	Explanation
ALOS	Advanced Land Observing Satellite
ASAR	Advanced SAR
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CFL	Calving Front Location
DARD	Data Access Requirements Document
DEM	Digital Elevation Model
ECV	Essential Climate Variable
ENVISAT	ESA Environmental satellite
EO	Earth Observation
ERS	European Remote-sensing Satellite
ESA	European Space Agency
ETM+	Enhanced Thematic Mapper plus
GMB	Gravimetric Mass Balance
GIS	Geographic Information System
GIS_cci	Greenland_Ice_Sheet_cci project, short form
GrIS	Greenland Ice Sheet
GLL	Grounding Line Location
GRACE	Gravity Recovery and Climate Experiment
GRACE SDS	GRACE Science Data System
InSAR	Interferometric SAR
IS	Ice Sheets
IV	Ice Velocity
LANDSAT	Land Remote Sensing Satellite
NASA	National Aeronautic and Space Administration
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PG	Product Generation
PSD	Product Specification Document
PV	Product Validation
PVP	Product Validation Plan
RA	Radar Altimeter
RR	Round Robin
SEC	Surface elevation Change
SAR	Synthetic Aperture Radar
TM	Thematic Mapper
URD	User Requirement Document

1 Introduction

1.1 Purpose and Scope

This document is the 4th Climate Assessment Report (CAR), summarising the work carried out over the 2nd phase of the 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 Climate Assessment Systems within the GIS_cci project, as part of ESA Climate Change Initiative (CCI) programme. The original document was based on the Phase 1 Climate Assessment Report (CAR) [RD2], of the "Ice_Sheets_cci" project.

This document incorporates earlier work from previous CARs but has been significantly updated with new use cases of the Greenland ice sheet data by the scientific community. We have added a section on the inclusion of GIS_CCI data in international reports, and we also report on some new planned activities where there will be further analysis of produced datasets in collaboration with the climate modelling 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.

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.

There are five parts:

- Background and overview of data products
- Important results from the climate research community
- Implementation of ECVs in models
- Outreach and Communication
- Recommendations for future work and possible case-studies.

1.2 Background

As the ESA Climate Change Initiative moves into the second decade of operations, it is worth taking some time to reflect how the scientific landscape has changed. At the end of the 20th century, the consensus was that the Greenland ice sheet was stable and more or less in balance and that there would likely be relatively few changes in ice sheet properties like melt rates, velocities or calving rates for many decades, as a result of climate change. The wide availability of Earth Observation data dramatically changed this view in the early 2000s with multiple glaciers seen to accelerate and retreat in dramatic calving driven episodes. Since then, ice shelves around Greenland have fragmented and collapsed, widespread surface melt episodes were documented in 2002, 2010, 2019 and most dramatically of all in 2012. Mass loss rates have proven to be sustained over the last twenty years, in spite of local and process driven variation. Through this period the development of open-datasets and easy availability of EO data have been key to early warning of dramatic changes as well as long-term monitoring of mass budgets, improvements in process modelling and the development of a theoretical framework around ice sheet dynamics.

At the same time, developments in ice sheet surface mass budget and ice dynamical modelling have also leaped ahead, though these have not yet caught up with developments in EO data as analysis by Aschwanden et al., 2022 clearly shows. In Figure 1, the ice sheet models used in the ISMIP6 (Ice Sheet Model Intercomparison Project for CMIP6 - the sixth climate model intercomparison project) are compared with observed rates of mass loss for Greenland. Clearly, most ice sheet models are underestimating the rate at which ice is being lost from Greenland when compared with observations. There are likely many reasons for this, ranging from underestimation of SMB to low resolution of models, limits on effective initialisation, unclear parameter choices in the ice sheet models and the poor representation in general of calving and ocean interactions.

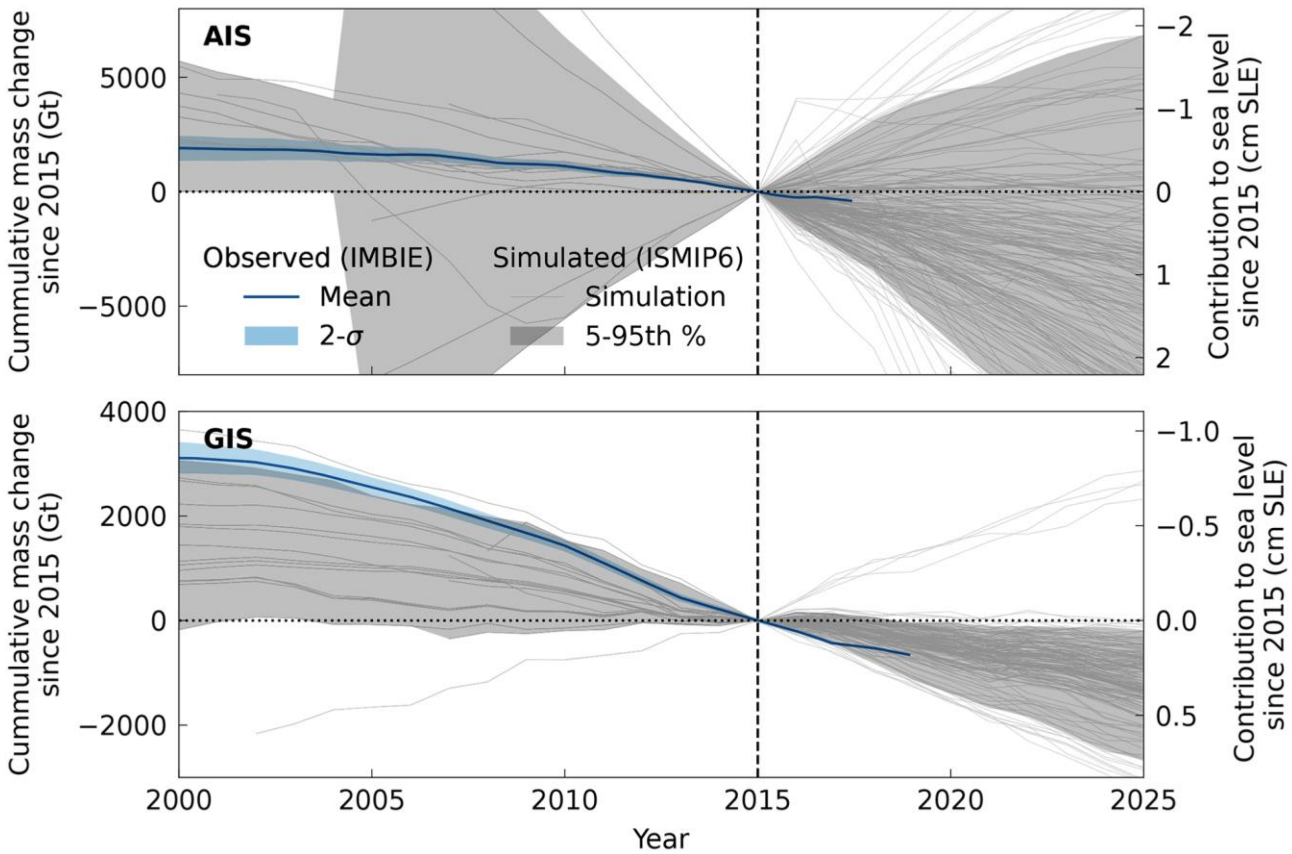

Figure 1. from Aschwanden et al., 2022 Observed and simulated historical mass changes from the Antarctic ice sheet (AIS) and Greenland ice sheet (GIS) between 2000 and 2020 in gigatons (Gt) and centimeters of sea level equivalent (cm SLE). A consensus estimate of observed mass changes (The IMBIE team, 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.

Resolving these issues to be able to better match historical observed ice sheet loss via improved process understanding will require more access to EO and field observational datasets and at a finer spatial and temporal resolution in coming years.

The response of the Greenland Ice Sheet to current and future climate change is a matter of great concern, not only to the scientific community but to society as a whole due to the consequences for sea level rise globally and regionally. Massive efforts have been and continue to be undertaken to understand and model the dynamics of the Greenland Ice Sheet and its interaction with the climate system. Uncertainties around the ice sheet response to climate change were explicitly addressed in the IPCC 5th and 6th Assessment Reports (Vaughan et al., 2013) as well as the Special Report on Oceans and the Cryosphere.

In support of reducing uncertainty about observed ice sheet changes and enhancing process understanding that will contribute to better future projections, the best possible evaluation data as well as reference data sets that can serve as boundary conditions and boundary constraints are in demand by the scientific community. Here, we assess the use and application of the GIS_cci products and show some examples of where the Essential Climate Variables (ECVs) have been applied scientifically. Building on the past years of effort, the GIS_CCI is now in a "harvesting" phase with many interesting projects and publications using the ECVs from the CCI, in spite of recent disruptions to the scientific process posed by the COVID19 pandemic.

Previous versions of this report have already shown how analysis of the ECVs has thrown up some surprising data that will likely lead to enhanced models in the future, as well as scientific publications exploring how models and observations can be used constructively together. In this report we give some new examples and case studies, including an overview of the use of GIS_cci data in the most recent IPCC and AMAP reports as an additional sub-section. The use of ECVs to evaluate models and for process studies is explored in Section 4. We also give some suggestions on future possible uses of the ECVs and widen out the target group of users to include some large international collaborations and projects that will use CCI data sets as a result of specific targeting by ESA_CCI consortium members..

We also note that the use of the data to produce graphics and visualisation that are widely shared on social media platforms is also becoming an increasingly important part of scientific communication efforts generally. Although not an original part of the scope of this report, the value of the ECVs as a science communication tool should not be underestimated and in future we will also attempt to track the non-scientific use of these products to produce easy to follow climate information for the public. In particular we note the recent launch of the QGreenland GIS tool which also incorporates GIS_CCI data and which will be helpful in further promoting the use and applications of GIS_CCI datasets. (see section 5)

Overall, the CRG finds that the published and unpublished results outlined in this document give an indication of the successful application of the GIS_cci data products within the limits of the errors of both the GIS_cci data product-based estimates and the independent data errors.

1.3 Reference Documents

Table 1.1: List of Reference Documents (latest versions available on the CCI web site)

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
RD1	ESA-CCI-EOPS-PRGM-SOW-18-0118, Appendix 2 to contract.	Climate Change Initiative Extension (CCI+) Phase 1, New R&D on CCI ECVs Statement of Work	31 May 2018	Issue 1 Revision 6
RD2	ST-DTU-ESA-ISCCI-CAR-003	Climate Assessment Report (CAR)	Oct 2018	2.1
RD3	ST-DTU-ESA-GISCCI-URD-001	User Requirement Document (URD)	15 January 2021	2.1
RD4	ST-DTU-ESA-GISCCI-PSD-001	Product Specification Document (PSD)	19 March 2017	2.3
RD5	ST-DTU-ESA-GISCCI-DARD-001	Data Access Requirement Document (DARD)	23 November 2017	2.3
RD6	ST-DTU-ESA-GISCCI+-ATBD-001	Algorithm Theoretical Baseline Document (ATBD)	26 October 2021	1.4
RD7	ST-DTU-ESA-GISCCI+-CECR-001	End to End Uncertainty Budget (E3UB)	February 2020	1.1
RD8	ST-DTU-ESA-GISCCI+-SSD-001	System Specification Document (SSD)	6 July 2021	1.2
RD09	ST-DTU-ESA-GISCCI-SVR-001	System Verification Report (SVR)	18 October 2016	2.1
RD10	ST-DTU-ESA-GISCCI-PUG-001	Product User Guide (PUG)	25 February 2022	2.0
RD11	ST-DTU-ESA-GISCCI-PVIR-001	Product Validation and Inter-comparison Report (PVIR)	February 2021	2.1

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 for the utilization of existing Earth observation data by the research community have been removed.

The GIS_cci operationally produce four 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 now frozen (GLL and CFL). All of the current ECVs are of great relevance to the very diverse range of scientific fields and approaches that constitutes the climate research community in Greenland. While GLL is no longer particularly relevant given the loss of most of the floating ice shelves around Greenland, it is still possibly useful at a few outlet glaciers (notably Petermann and Humboldt as well as 79 Glacier). Given the continued retreat of calving fronts around Greenland, there is an argument for producing this dataset and making it available again; for the same reason an add-on CCN project has been carried out by S&T in order to demonstrate the use of machine learning for deriving CFL parameters.

For the purposes of this report we use the following abbreviations for the different ECV datasets:

- Surface Elevation Change (SEC)
- Ice Velocity (IV)
- Gravimetric Mass Balance (GMB)
- Mass Flow Rate Ice Discharge (MFID)
- Supraglacial Lakes (SGL)

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. 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. An overview of the ECVs and the status of the Greenland ice sheet was published by Mottram et al., (2019). Previous reports have highlighted as a few examples, Sørensen et al. (2011) who used SEC to quantify the mass loss from the Greenland ice sheet and Shepherd et al. (2012) compared results on ice sheet mass balance from different methods employing SEC, GMB and IV.

ECVs like SEC and IV have also been drivers of climate research, with observations leading to new breakthroughs and insights into the climate system, such as Rignot and Kanagaratnam (2006) who employed IV to document a change in the velocity structure of the Greenland ice sheet with dramatically increased contribution to sea level rise as a consequence. These approaches have been recently extended by for example, Simonsen et al., (2021) and Shepherd et al., (2020) to cover more recent changes in the Greenland cryosphere. On a process level, IV and SEC are now also being used together with surface mass balance and runoff output from models to quantify processes of mass loss on a fine scale (for example, Rathmann et al., 2017). They are also useful to identify new processes that have not previously been captured (for example, Solgaard et al., (2019) and Rosier et al., (in preparation) or have not been documented in different parts of Greenland. CFL and GLL have been used by e.g. Hogg et al (2016) and other references to track changes in outlet position and to assess if imminent retreat of an ice shelf is likely.

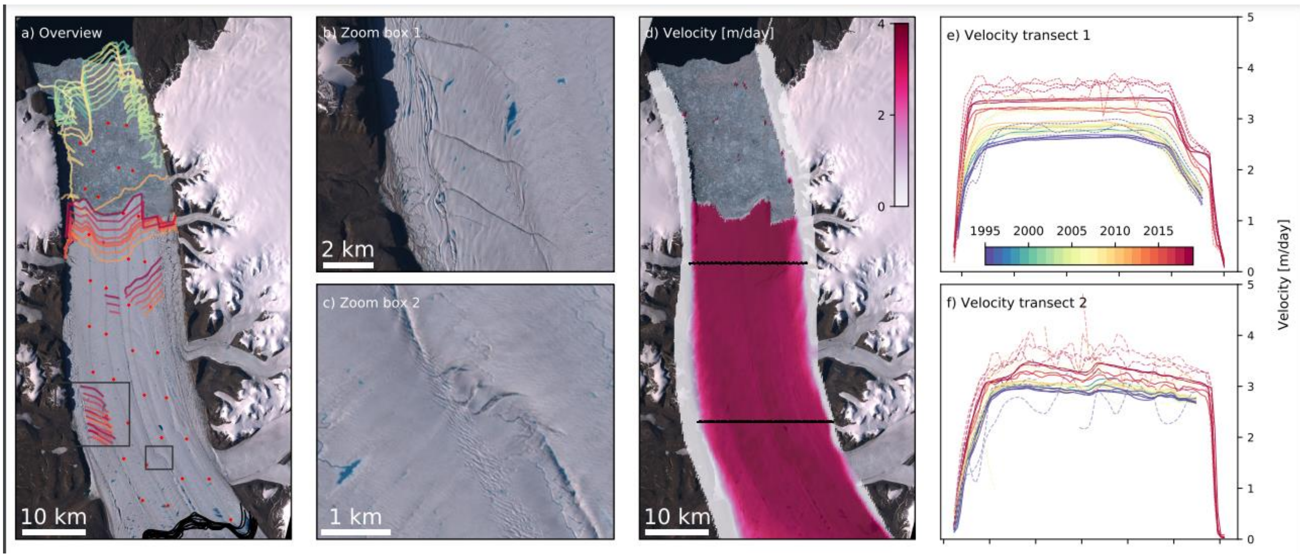

Figure 2. Rosier et al (in preparation) overview of Petermann Ice Shelf changes on a Sentinel-2 image from July 2018 showing a) historical Petermann Glacier calving front positions and initiation and development of new fractures (colour-coded per year), grounding lines from Rückamp et al. (2019) (black), and airborne radar transects (red-dotted lines); b-c) zoom boxes of a) showing the newly observed fractures; d) August 2017 Sentinel-1 velocities and lateral velocity transects; e-f) velocity time series along transects 1-2 for summer (dashed lines) and winter (full lines) showing the increased velocity gradients across the transects resulting in increased strain rates.

The addition of MFID updated on a rolling monthly basis (Mankoff et al., 2019) provides near real-time monitoring of ice sheet discharge due to ice dynamics that is innovative and was unimaginable ten years ago at the start of the CCI project. Building on IV, SEC and ice thickness, it is a blended dataset that successfully shows how different datasets can be used together to give a coherent picture of ongoing changes in Greenland.

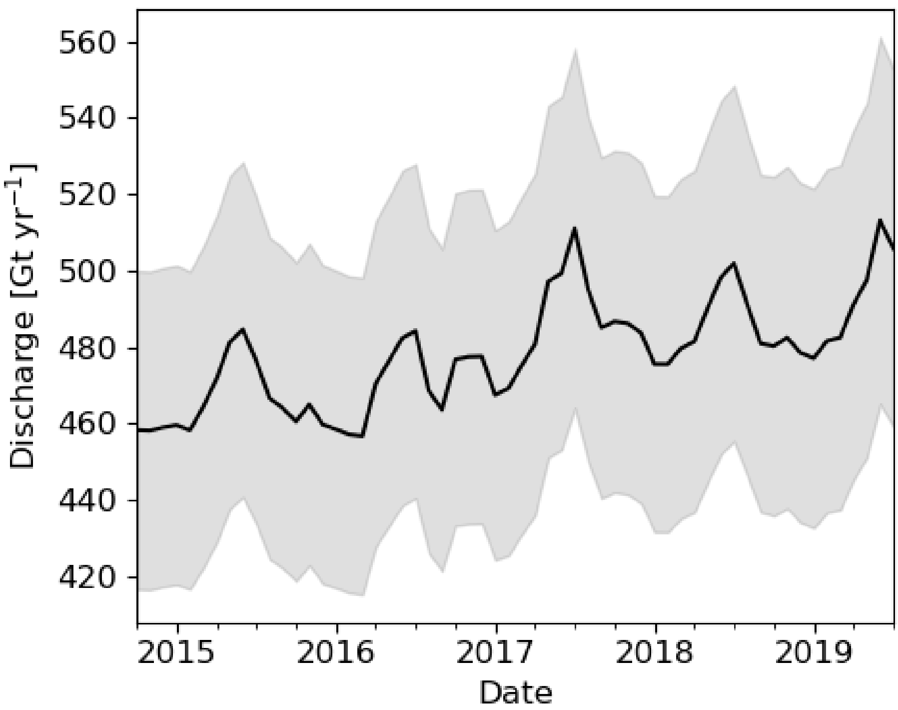

Figure 3 Mass flow rate ice discharge (MFID) product is derived from the CCI ice velocity (IV), the CCI surface elevation change (SEC), and ice thickness from BedMachine (v3).

Like MFID, the new Supraglacial Lakes (SGL) data product is also an innovative new data product that reflects recent advances in remote sensing and that also has practical applications for infrastucture, planning and local stakeholders. Supraglacial Lakes (SGL) are meltwater lakes on the surface of glaciers and the Greenland ice sheet that form in depressions in the ablation zone. Many of them are multi-year features but others drain and refill with an annual cycle. Supraglacial lakes are indicators of surface melt, but are also important for routing and storage of meltwater within the ice sheet system. They play an important role in the delivery of meltwater to the base of the ice sheet as the episodic nature of their drainage means there can be large amounts of water delivered over a short period to the base of the glacier. This has been observed to influence basal sliding on a range of spatio-temporal scales (e.g. Das et al., 2008). However, their role in the seasonal evolution of the subglacial drainage system is complex and related to specifics of each lake basin. The expansion of the area covered by surface lakes over the last 20 years (e.g. Leeson et al., 2015) is also a clear indicator of the ways in which climate change is affecting ice sheet surface melt processes.

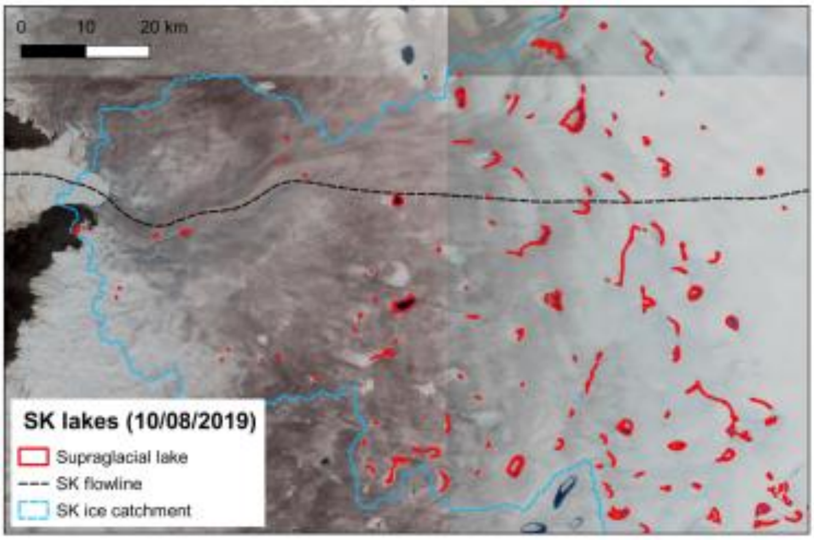

Figure 4 Supraglacial lakes mapped in the Sermeq Kujalleq (Jakobshavn Isbræ) catchment of western Greenland by Asiaq, a newly added data product in this round of the CCI.

Apart from the direct observation of ice sheet change provided by the ECVs, they also serve as input for inversion modelling of ice sheet parameters. In inversion models, information about the conditions at the base of the ice such as e.g. basal traction are inferred from observed surface conditions such as ice surface velocity of the ice sheet. Access to consistent, comparable time series of ECV products back in time is crucial in order for inverse models to produce reliable results. The use of ECVs in inverse modelling has provided a break-through in deriving the bedrock topography underneath the ice sheet margin and the outlet glaciers of the Greenland Ice Sheet (Morlighem at al., 2014). They have also elucidated fundamental questions such as geothermal heat flux (Colgan et al., 2021) and the consequences of enhanced ice sheet runoff to North Atlantic circulation (Lohmann and Ditlevsen, 2021) . Application of this improved bed topography in ice sheet models makes inverse modelling of other key parameters such as basal traction much more feasible. Recent developments in inverse modelling that attempt to use transient model runs with ECVs as constraining factors in the model over time show promise but results indicate that these model runs are still hampered by incomplete data (e.g. Aðalgeirsdóttir et al., 2014; Aschwanden et al., 2013, Gregory et al., 2021). On the other hand, the ECVs still represent the best possible data for constraining parameter choices in order to improve, model initialisation (Lee et al., 2015). This type of inversion requires temporally consistent ECV data, and as Aschwanden et al. (2013; 2019) show spatially dense observations are the preferred metrics for the use of hindcasting in order to assess modelled rates of change.

The ISMIP6 modelling exercise (Ice Sheet Model Intercomparison Project for CMIP6) has not so far systematically applied ice sheet ECVs but the next round (ISMIP7) is likely to lead to a more coordinated set of experiments. The participating ice sheet modelling groups are an obvious user-group for the ECVs to use in inversion modelling as part of the suite of experiments planned for the collaboration (for example, Price et al., 2017; Goelzer et al., 2017) as well as for evaluation of model runs.

Figure 5 shows results from the model intercomparison. The systematic use of the IV dataset to evaluate and tune these models will prove helpful in parameter sensitivity studies (e.g. Aschwanden et al., 2019).

We suggest closer collaboration, in which the appointment ofISMIP6 steering group member Sophie Nowicki to the CRG is a promising way to encourage closer collaboration. Furthermore, the participation of both ESA CCI members and ISMIP6 contributors in the Horizon 2020 project PROTECT on sea level contributions from thecryosphere will assist in more widely disseminating data products.

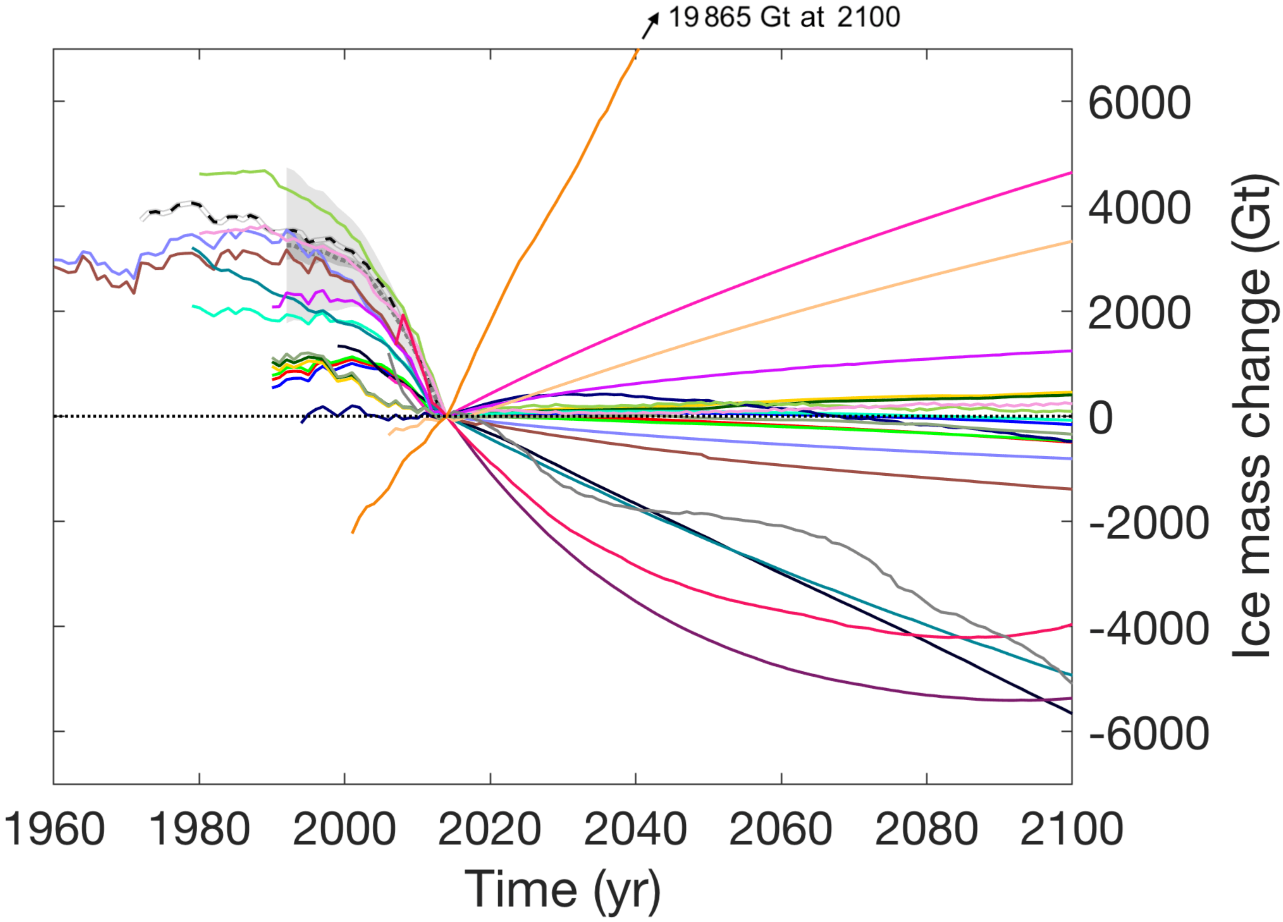

Figure 5. Goelzer et al, 2020 Ice mass change relative to the year 2014 from a range of ice sheet models for the historical run and experiment ctrl_proj. Recent reconstructions of historical mass change (The IMBIE Team, 2019) are given as a dotted grey line with cumulated uncertainties assuming fully correlated and uncorrelated errors in light and dark shading, respectively. The dashed black-and-white line shows one specific reconstruction going back longer in time (Mouginot et al., 2019).

3 State of Greenland: Important results on ice sheet mass budget

One of the most important uses of CCI data (for both ice sheets) has been in constructing a coherent overview of the state of mass balance of the cryosphere. In section 4 we focus more closely on the different potential uses to the scientific community of the CCI datasets to study ice sheet processes, but first we summarise the observed changes to the ice sheet mass budget, topography and extent.

3.1 Deriving mass balance from ECVs

The landmark IMBIE (Ice sheet Mass Budget Intercomparison Exercise) paper (Shepherd et al., 2020) assembled a number of datasets that together showed the decline in ice mass of the GrIS. This paper followed Shepherd et al (2012) in assembling different types of data to assess mass budget and the different components driving changes.

Overall, Shepherd et al. (2020) found a total mass change of some 4000 Gigatonnes since 1991 with a marked increase in ice loss since the early 2000s.

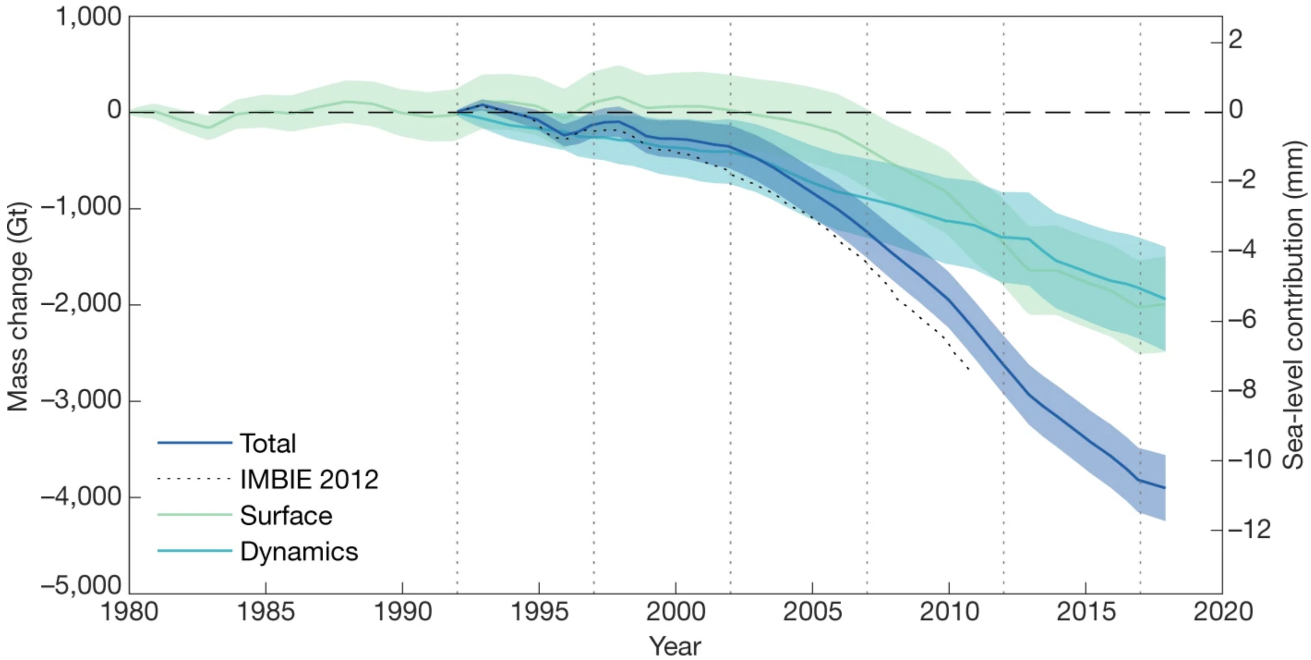

Figure 6 Cumulative ice sheet mass budget for Greenland from Shepherd et al. (2020) divided into surface and dynamic components and including contributions from the GIS_CCI consortium.

The GRACE and GRACE-FO missions used for the GMB ECV are central to this analysis and different solutions were presented in the study. GMB fills an important niche in the assembly of the Greenland Ice Sheet ECVs, being the only "integrated" product which can give the overall mass balance of all land ice masses in Greenland, and thus the important boundary condition to current sea level rise. Although it is acknowledged that GMB in Greenland also has error sources, especially the separation of Canadian ice cap effects from Greenland effects (notably Ellesmere Island), it appears that the accuracy of GMB, currently estimated at the 10% level, represent a clear improvement of observability. It is an integral measure to which the other techniques (SEC derived and Input-Output method mass balance estimates) will ultimately have to agree with, at least within the given errors.

In addition to the GMB, IV and MFID data were used alongside results from regional climate models. The combination of the ECVs and models is particularly powerful. Figure 7 below compares the SEC ECV results from the CCI with MSB output from HIRHAM5 – this plot is similar to one presented in Mottram et al., (2019). Around the margins, the enhanced ice loss depicted by the red colours is a combination of both SMB and ice sheet dynamical processes. The RCMs do not calculate the latter and the SEC processing suggests that they may underestimate the amount of snowfall in central Greenland. Overall the SEC data supports the modelled SMB values. It is however, important to note that the two are not totally independent datasets. RCM outputs of e.g. temperature and precipitation are required to account for the effects of densification in snow pack. However, the combination of ECVs also allows process studies to disentangle different effects (see next section).

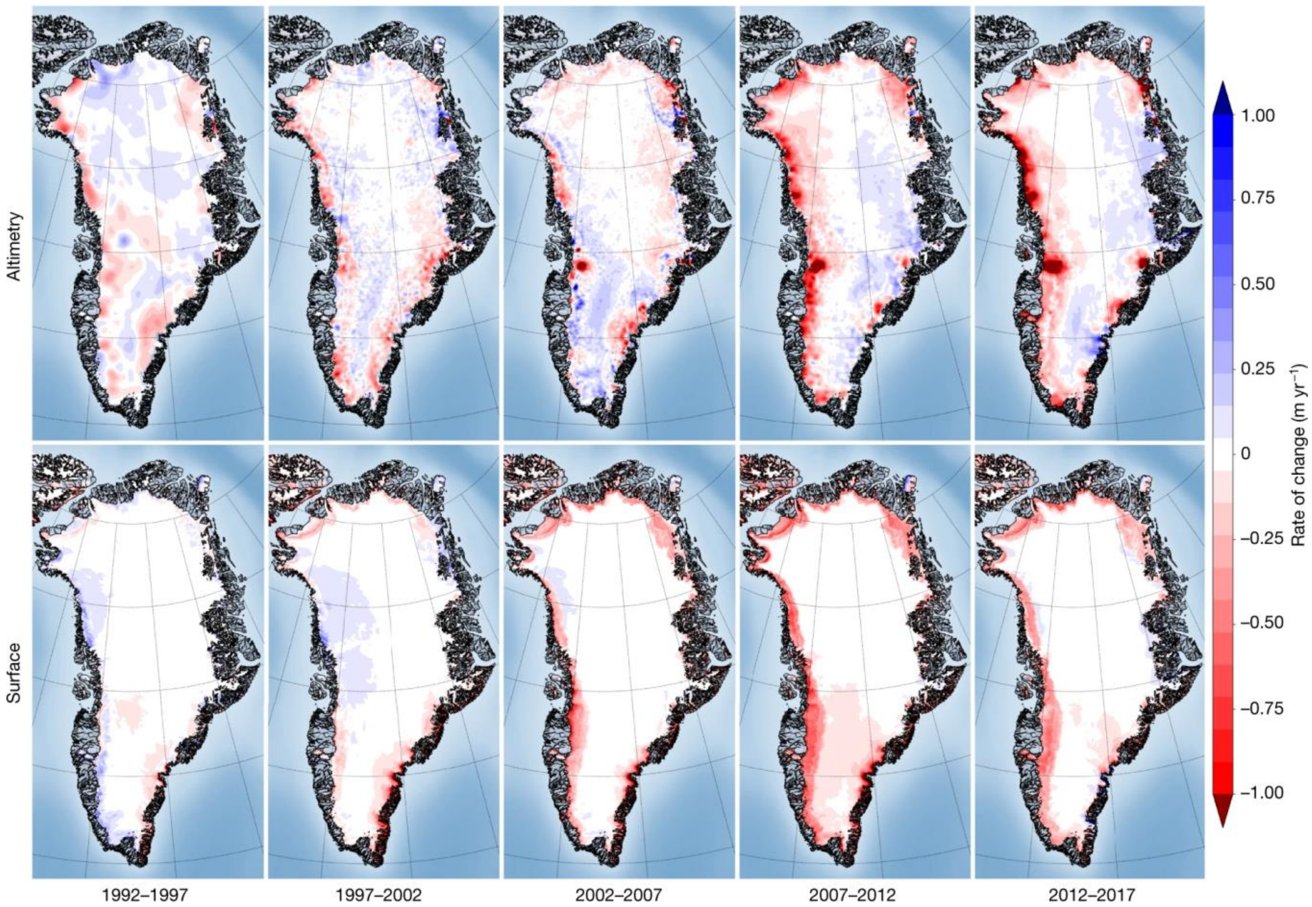

Figure 7 Observed SEC and modelled SEC derived from the HIRHAM5 regional climate model, from Shepherd et al., 2020.

The mass balance derived from SEC estimates is not trivial to produce due to the complications of firn compaction, signal penetration, sloping surfaces and variable topography as well as shortcomings in spatial coverage. A further advantage of the IMBIE process therefore is the possibility to compare different datasets with each other to assess what the spread in estimates is likely to be. Shepherd et al (2020) show both GMB and SEC intercomparisons, from which it is clear that GIS_CCI ECVs are consistent with other estimates within the community. The consistent long-term semi-operational production of the ECVs is therefore immensely valuable in a monitoring role of the Greenland ice sheet. Figure 8 below is reproduced from Shepherd et al. (2020) and shows the ECVs in context with other datasets for both altimetry and GMB.

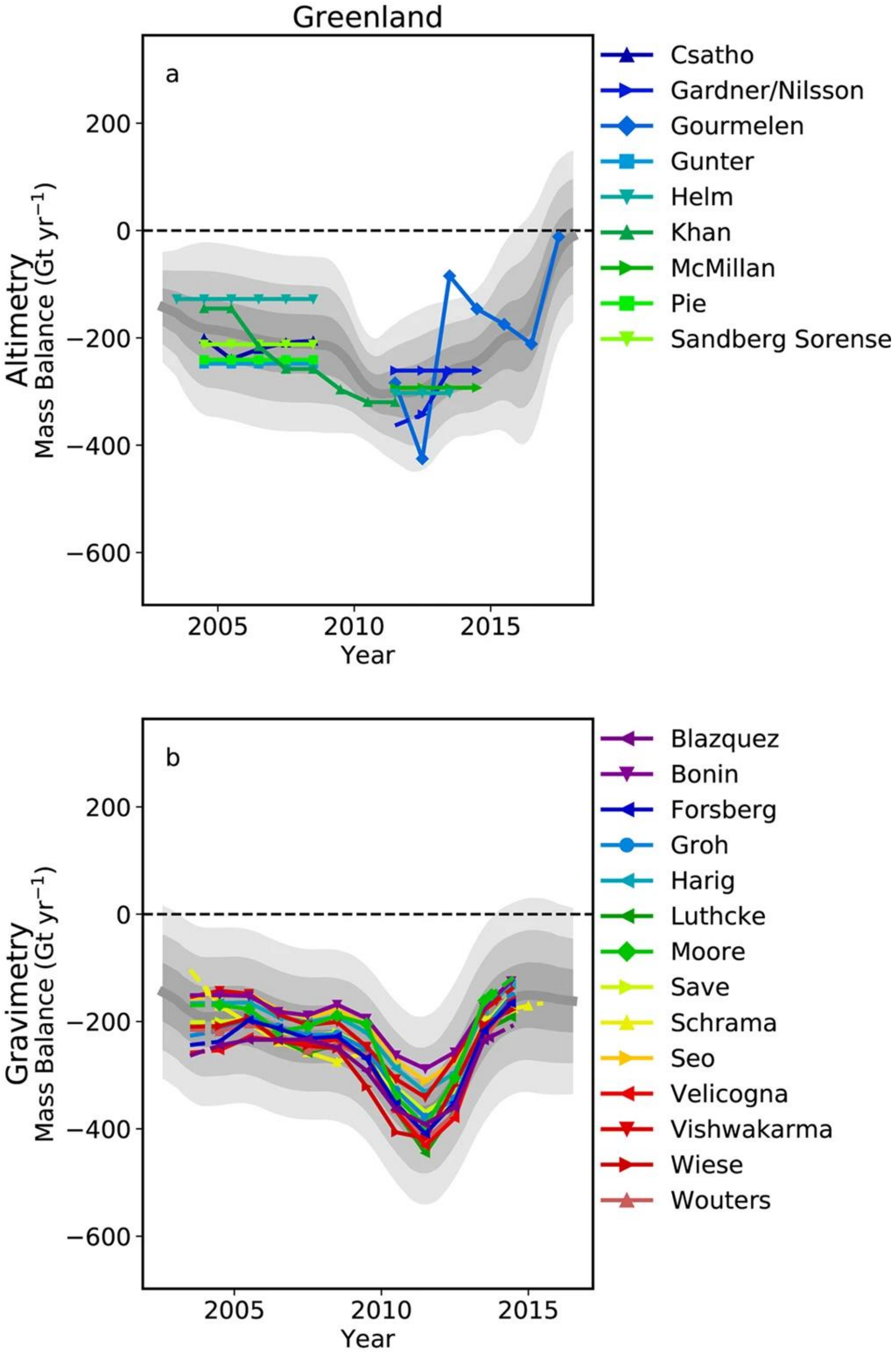

Figure 8 Altimetry and gravimetry data for the Greenland ice sheet included in the IMBIE analysis of Shepherd et al., (2020)

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Given the challenges listed above in interpreting SEC for mass balance estimates, new developments (Sørensen et al., 2015; Levinsen et al., 2015) are crucial. These include an enhanced understanding of the firn densification process (Vandecrux et al., 2020; Hansen et al., 2021). Capturing the densification process is crucial, especially as this process is highly climate dependent and thus undergoing change over time. Over the same region, a laser altimeter might observe a surface lowering, while a radar altimeter observes a rising reflection horizon. The actual mass change may in turn be derived from space-borne gravimetry, but at a very low resolution and with significant uncertainties. Combining different types of satellite data (including the ECVs produced in the IS-CCI), validated with ground observations, is probably the most viable path for deriving the contribution to sea level change by the Greenland Ice Sheet. In a new GIS_CCI paper Simonsen et al. (2021) combine both laser and radar altimetry to do just this.

The new 28 year Greenland Mass budget (see Figure 9) is compared with GMB and MFID ECVs as an external check on the process. This new study is particularly valuable as it covers the exceptionally high melt year of 2019 and the return to slightly more average conditions in 2020 that were not covered by the Shepherd et al (2020) IMBIE study. Simonsen et al. (2021) among other results show that high snowfall in October 2016 followed by a relatively cool summer in 2017 produced the first and so far only positive or neutral mass budget year since 2000. Although reported at the time on the polarportal (www.polarportal.dk/english), these results based on remote sensing observations confirm the initial estimates and give us enhanced confidence in the modelled SMB approach for near real-time monitoring using weather and climate models.

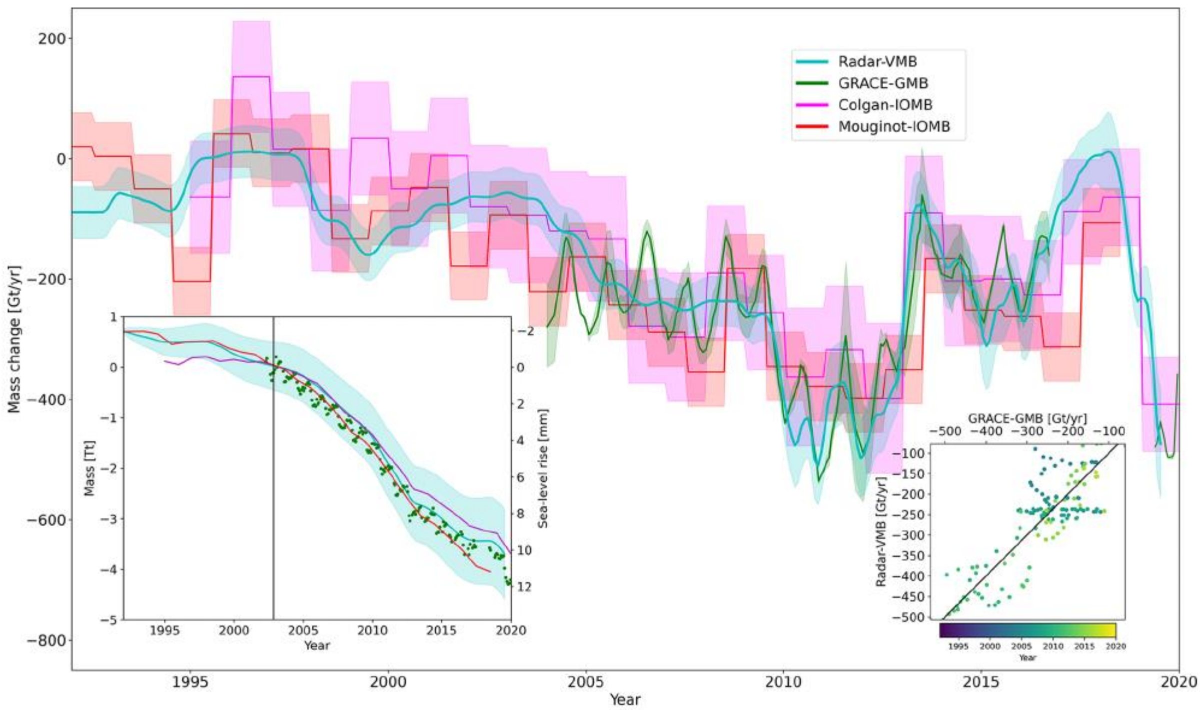

Figure 9: Greenland ice sheet mass change derived from calibrated altimetry by Simonsen et al. (2021)

A further conclusion of the Simonsen et al (2021) study is the focus on the importance of spatial variability in Greenland. The positive mass balance year in 2016/2017 is a result of summing SMB over the whole of Greenland, but mass input from snowfall was focused very much in eastern Greenland. The weather systems that brought this snowfall were two atmospheric rivers bringing large amounts of precipitation direct from the tropics and associated with two extra-tropical cyclones (the former hurricanes Nicole and Matthew). These events were sufficient in aggregate to offset the summer melt season but the western part of Greenland still experienced a relatively high mass loss due to summer melt and Figure 10 shows that even though Eastern Greenland received a large amount of additional precipitation, it was not sufficient to push the ice sheet into a significantly positive balance.

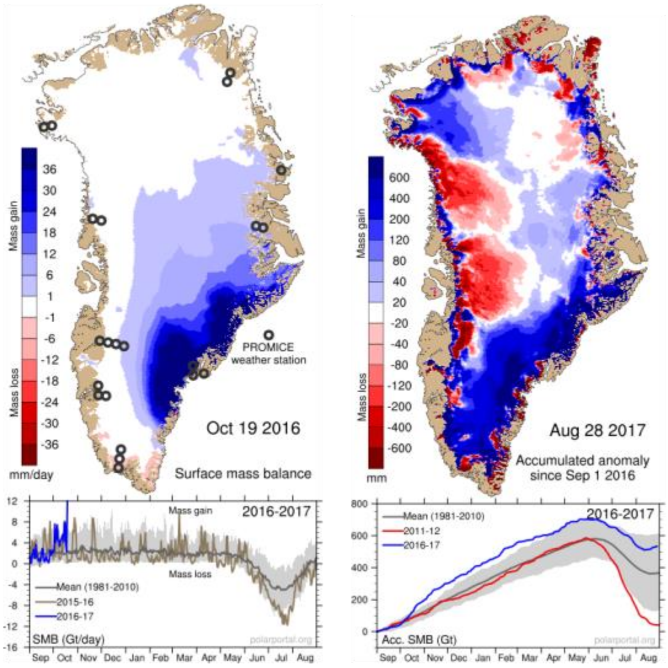

Figure 10 Surface Mass Balance of Greenland as presented on polarportal.dk and calculated using numerical weather prediction model HIRLAM and the SMB model developed at DMI. On the left the daily value for the 19th October 2016, which was the highest accumulation event that year and a record for the community of Tasiilaq in south-east Greenland where precipitation measurements have been made since the 1950s. The right plot shows the anomaly in SMB for the 2016-2017 SMB year compared to the 1981-2010 climatological period.

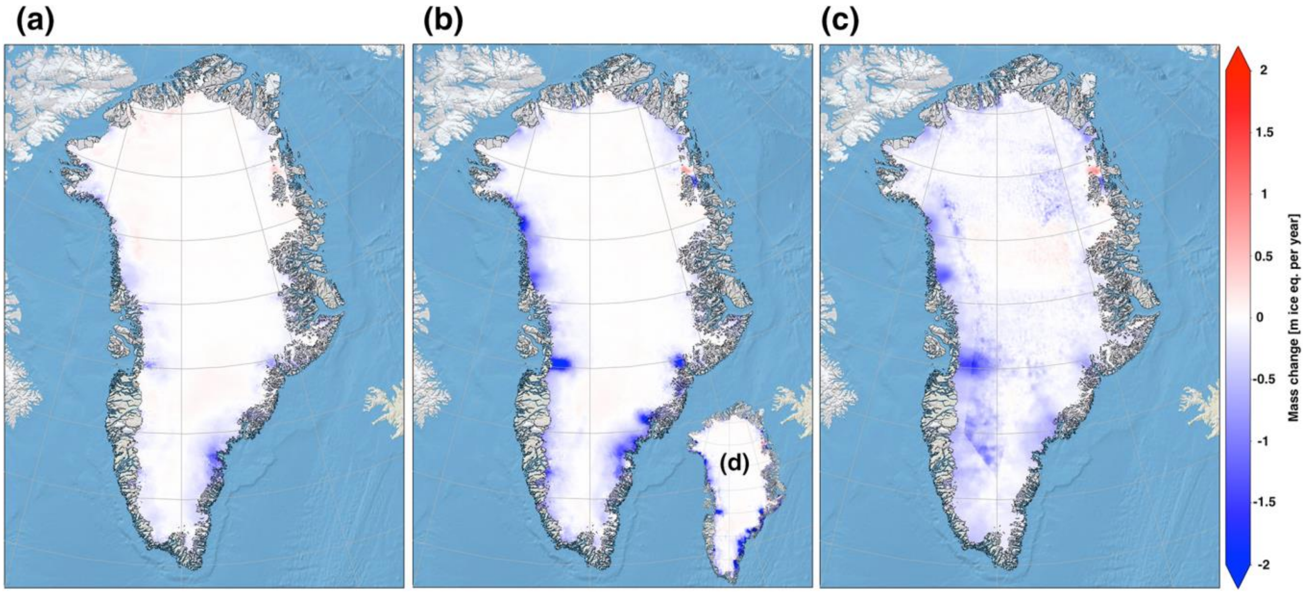

Figure 11 from Simonsen et al., 2021. Satellite radar-altimetry mass balance. (a) the early period 1992–1999, with only limited mass loss at the outlet glaciers. (b) The 2000s, whereas the insert (d) showing the spatial distribution of the ICESat-VMB (2003–2009). Compared to the 1990s the accelerating mass loss of the GrIS is clearly visible. (c) The later period 2010–2020, which show a continuation in the mass loss, with the outlet glaciers in the Baffin-area showing the speed-up in the mass loss

The importance of high magnitude but low frequency events in mass budget has been examined in both for Antarctica (and Greenland, with ood work by (Mattingley et al, 2018). The large amount of snow deposited in south east Greenland during October 2016 (see Figure 10, calculated using the HIRLAM weather forecast model and SMB model run at DMI and shown on polarportal.dk) was sufficiently anomalous to dominate the mass budget for the year. The mass budget year runs from 1st September to 31st August with the accumulation processes largely dominating from September to May and ablation processes mostly dominating for the 3 summer months of June, July and August. The analysis presented in Simonsen et al., 2021 shows considerable promise for the technique in helping to assess surface mass budget estimates from models in near real-time. Accumulation estimates in particular are hard to observe with in-situ measurement but have a disproportionate impact on SMB due to the effects of albedo feedback related to snow melt (e.g. Hermann et al., (2019).

The data sets produced within phase 1 of the project were made available for download in summer 2015, with updated and extended data sets made available until early 2022. The download statistics of the data archive up to Q1 2022 are shown in Figure 12

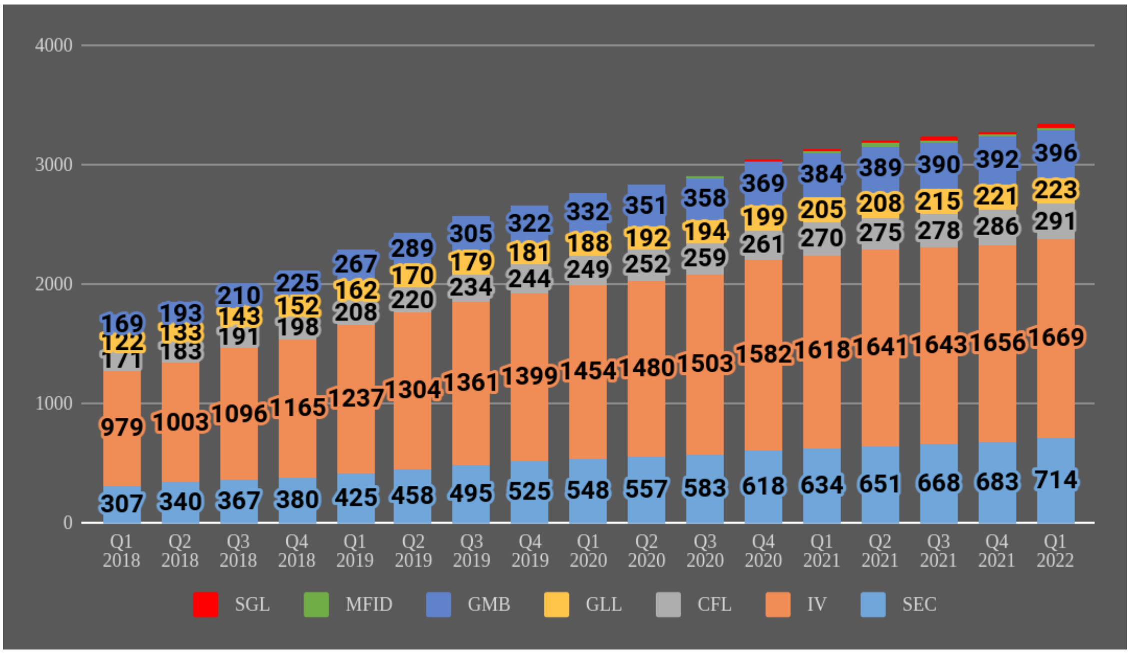

Figure 12 Cumulative downloads of data products and total numbers per Q4 2020 from the project website (http://products.esa-icesheets-cci.org/).

The GIS_cci ECVs were widely cited in the IPCC report with focus on ice sheet mass changes both integrated and from the different components. The summary for policymakers states explicitly that "it is very likely that human influence has contributed to the observed surface melting of the Greenland Ice Sheet over the past two decades, but there is only limited evidence, with medium agreement, of human influence on the Antarctic Ice Sheet mass loss" (IPCC 2021 Summary for policymakers, p.5), based on GIS_cci studies referenced in the report. The technical summary also shows both altimetry data and the mass loss partitioning into surface melt and the ice dynamics component as highlight, see for example Figure 13 from the IPCC 6th Assessment Report technical summary. Updates in estimates of Greenland ice sheet mass loss since the special report on oceans and the cryosphere are also mentioned as important parts of the report (IPCC 2021b).

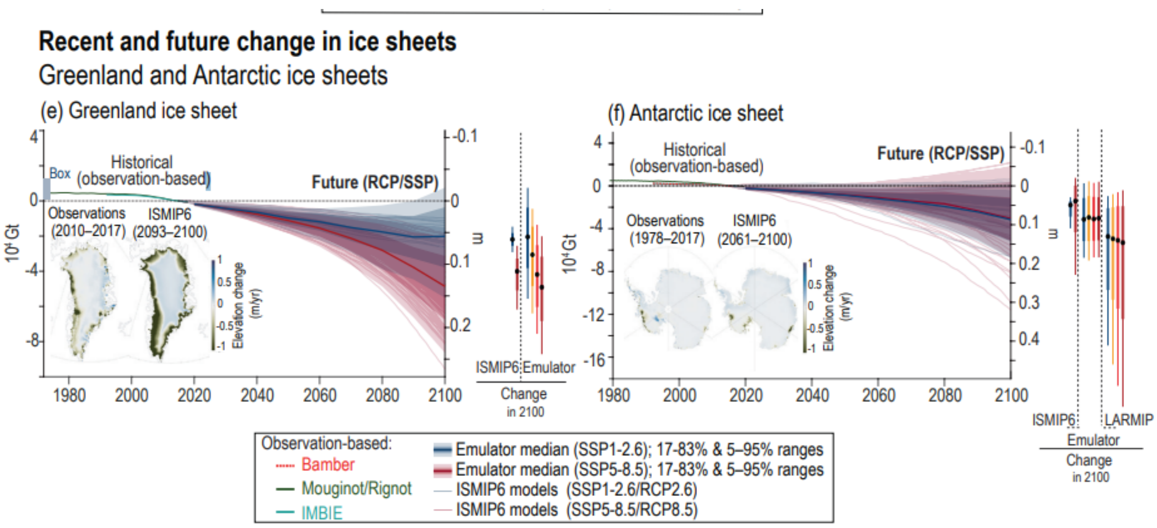

Figure 13: IPCC Working Group 1 of the sixth Assessment Report Technical summary Figure TS.11 | Past and future ocean and ice-sheet changes. : Ice sheet mass changes. Projected ice-sheet changes are shown as

median, 5–95% range (light shading), and 17–83% range (dark shading) of cumulative mass loss and sea level equivalent from ISMIP6 emulation under SSP1-2.6 and SSP5-8.5 (shading and bold line), with individual emulated projections as thin lines. Median (dot), 17–83% range (thick vertical bar), and 5–95% range (thin vertical bar) in 2100 are shown as vertical bars on the right-hand side of each panel, from ISMIP6, ISMIP6 emulation, and LARMIP-2. Observation-based estimates: For Greenland (e), for 1972–2018 (Mouginot), for 1992–2016 (Bamber), for 1992–2020 (IMBIE) and total estimated mass loss range for 1840–1972 (Box). For Antarctica (f), estimates based on satellite data combined with simulated surface mass balance and glacial isostatic adjustment for 1992–2020 (IMBIE), 1992–2016 (Bamber), and 1979–2017 (Rignot). Left inset maps: mean Greenland elevation changes 2010–2017 derived from CryoSat-2 radar altimetry (e) and mean Antarctica elevation changes 1978–2017 derived from restored analogue radar records (f). Right inset maps: ISMIP6 model mean (2093–2100) projected changes under the MIROC5 climate model for the RCP8.5 scenario.

4 Process Studies

As section 3 demonstrated, the use of ECVs to determine Greenland ice sheet mass budget and monitor ongoing changes is extremely valuable. To prepare for future impacts of climate change such as sea level rise, it is necessary to incorporate ice sheet processes into climate and ice sheet models in order to produce accurate projections. Climate and ice sheet modelling is done on a whole range of temporal and spatial scales and model types, ranging from stand-alone ice sheet models to coupled earth system models. Regardless of the type of model, a correct representation of the ice sheet is of crucial importance to model performance. The CCI data products can be used to define both the initial states as well as providing constraints over the course of a model simulation (Price et al., 2017). However, arguably the more important use of ECVs in the last few years has been in process studies aimed at defining model biases and uncertainties in processes that underpin both surface mass budget and ice sheet dynamical processes.

4.1 Ice Sheet Surface Processes

Surface elevation change (SEC) data has so far been produced covering the entire ice sheet at a grid resolution of 5km. Maps of SEC covering the entire ice sheet are a major asset when evaluating the performance of both stand-alone ice sheet models and ice sheet modules in coupled climate models. Surface elevation changes from model runs driven by historical climate conditions may be compared to the cci SEC data, thereby providing valuable knowledge about model performance and increased confidence in projected values of SEC from scenario-driven runs (e.g. Aschwanden et al., 2013; Adalgeirsdottir et al., 2014; Lee et al., 2015).

In Figure 14 (from Mottram et al., 2019) for example, the comparison of SEC (top row) with SMB model output (central row) and ice sheet model output driven by the same SMB model (bottom row) for different periods reveals important details. For example, while the SMB model reproduces many of the broad mass loss patterns in the margins, the ice sheet model and ice dynamics are required to explain the large areas of drawdown around rapid calving outlets such as Jakobshavn Isbræ. However, the comparison also reveals mismatches, likely related to model inadequacies and low resolution, in areas where SEC shows large surface decreases that are not captured in the ice sheet model.

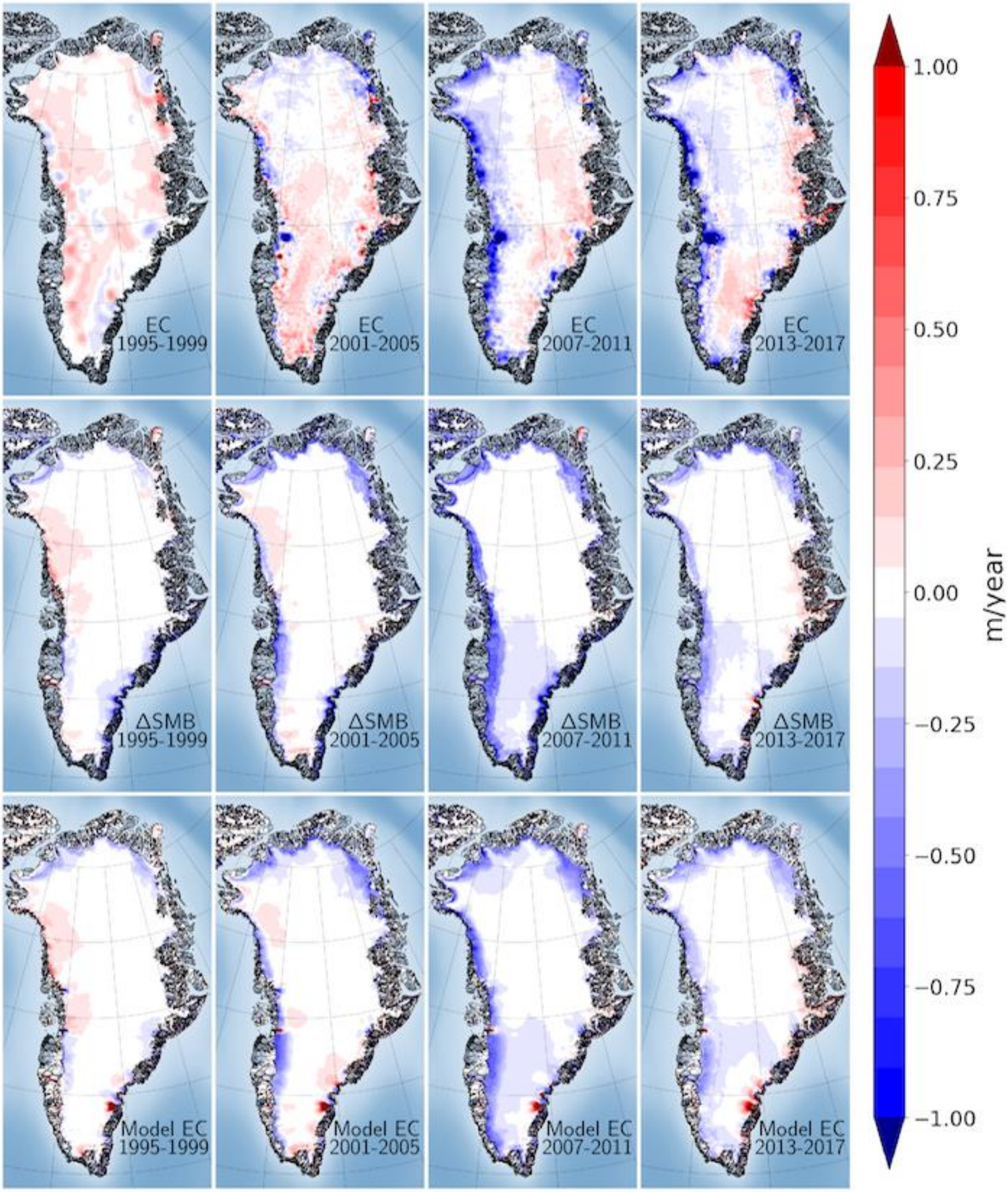

Figure 14 (Upper panel) Surface elevation of the GrIS from radar altimetry. (Middle panel) Change in surface mass balance in respect to the reference period (1982-1992) from HIRHAM5. (Lower panel) Change in volume as modelled by PISM when forcing PISM with HIRHAM5 surface mass balance and temperature.

The resolution allows for main features of the ice sheet to be visible, but many of especially the smaller outlets are on a spatial scale of only a few kilometres and are therefore be insufficiently resolved in the present data products. Increasing the spatial resolution further would be advantageous as for example, Aschwanden et al. (2013) find dense observations to be most useful for model inversion. As variable resolution grids become more popular in ice sheet models as well as climate models, higher resolution will become more important.

The same is true for using the SEC product for pre-feasibility studies for hydropower and mining projects along the ice margin. In this case, numerical modelling of the ice flow is usually done on higher resolution than 5km and model runs are only performed on relevant sections of the ice sheet. For these applications, the resolution is sub-kilometer, but would be well-informed with an SEC product of e.g. 1km as this would resolve the main features of the ice marginal area, such as outlet glaciers and effects of protruding nunataks on ice flow.

Similarly, atmospheric regional climate modelling is now breaching the 5km resolution and producing simulations at kilometre scale. A prime example of this is the Copernicus Arctic ReAnalysis (https://climate.copernicus.eu/tenders/copernicus-c3s322-regional-climate-reanalysis) (CARRA) project that aims to produce surface mass balance and related ice sheet components as part of a comprehensive new climate reanalysis for the Arctic. The reanalysis is now available for download on the climate data store and will, when finished, cover the period 1991 to 2022 at a resolution of 2.5km and will be extended to be pan-Arctic at around 3km resolution in a new future version. The SEC resolution is lower resolution but will still be useful resolution for the CARRA project to use as evaluation and the combination of both CARRA and SEC is powerful for process studies (see also case studies section below)

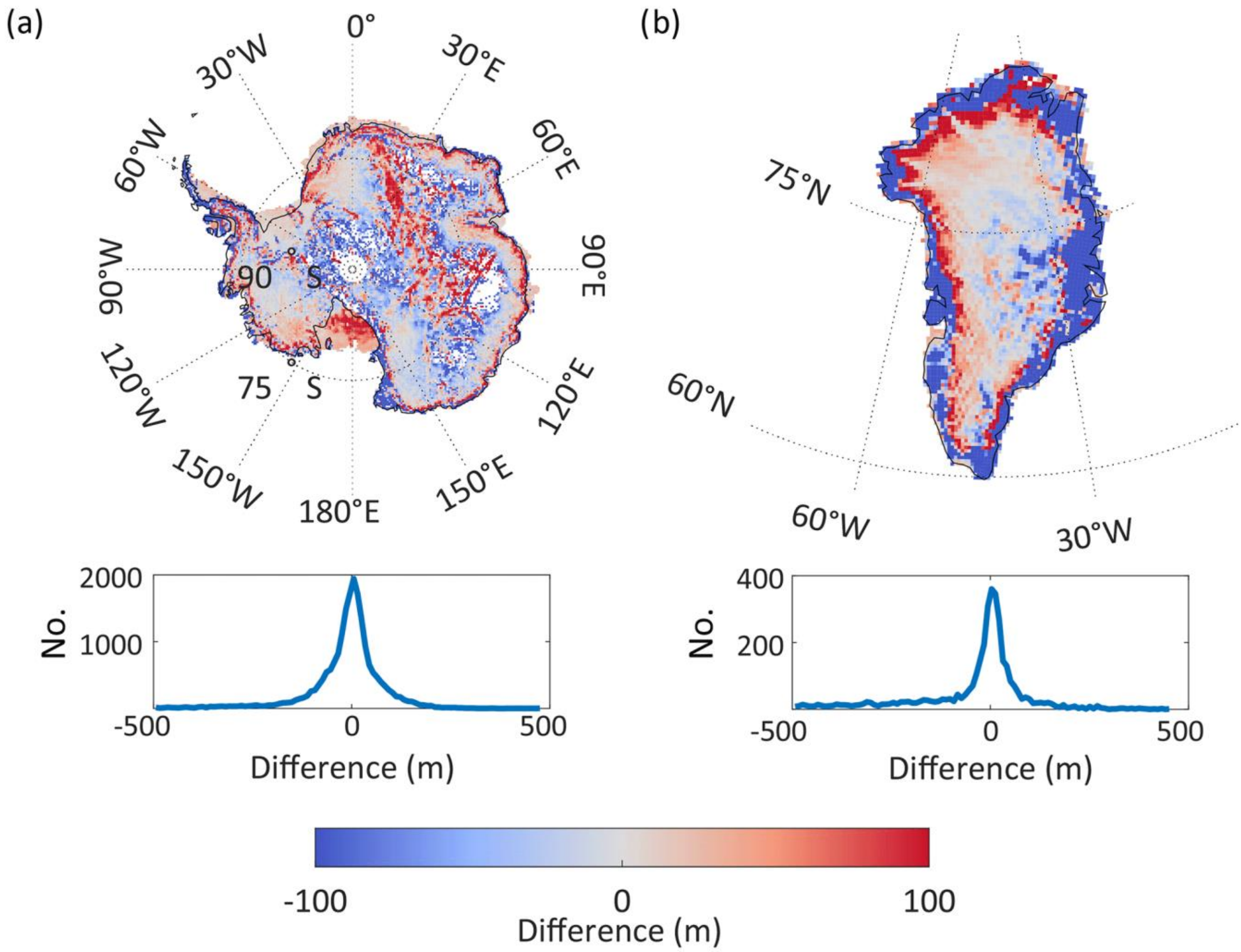

Figure 15 Figure taken from (Cartwright et al., 2020) Error maps over (a) Antarctica and (b) Greenland with respective histograms. The error shown is the comparison DEM subtracted from TDS-1 DEM. Comparison DEMs are the CryoSat-2 v1 1km DEM (Slater et al ., 2018) and the GL-CCI for (a) and (b) respectively. For further details please see Cartwright et al., 2020.

Other techniques that are in development have also used the CCI SEC product. For example, Cartwright et al.(2020) have used the CCI DEM and SEC product to develop a new GNSS based altimetry product based on data from the Tech-DemoSAT1. Combining the new GNSS observations with SEC will greatly extend the temporal and spatial resolution of SEC in the future and allow it to be used as a data assimilation product in ice sheet and NWP models. Several studies have been published recently where the CCI Greenland ice sheet topography has been used as a dataset in its own right to constrain ice sheet processes such as basal meltwater production (e.g. Karlsson et al., 2021).

4.2 Ice velocity IV

The ice velocity ECV is one of the most commonly cited in the published literature with new studies including Solgaard et al. (2021) and Winton et al (2021) adding to those already out. In the latter study IV data is used to determine basal stress during glacier surges at Hagen Bræ (see also Solgaard et al., 2020) and in the former a Greenland wide velocity map was produced.

The IV data really comes into its own however when it is used on the scale of individual outlet glaciers. For example, the individual times series of IV for Jakobshavn and Upernavik provide valuable material for understanding the dynamics of some of the most important and dramatic changes in the ice flow dynamics of the Greenland ice sheet in recent years and may form the basis of efforts in development and validation of ice sheet model dynamics. With the expansion encompassing 9 key ice streams (Hagen, Helheim, Jakobshavn, Kangerlussuaq, Petermann, Nioghalvfjerdsfjorden, Storstrømmen, Upernavik and Zacharias Isstrøm), the modelling community now has an essential data set to investigate ice flow dynamics. The issue of basal conditions and the relation to fast flowing ice streams is a critical point in understanding the ice sheet response to global warming and these high-resolution IV products are now proving to be an indispensable tool in research efforts to understand the dynamics of fast flowing ice streams (Aschwanden et al., 2016, Haubner et al., 2018; Winton et al., 2021). Another example of the use of high resolution IV for outlet glaciers in combination with the grounding line and calving front data sets as well as atmospheric is work by Rathmann et al (2017, see figure 16 below) that focused on the glaciers of the north east Greenland ice stream (NEGIS).

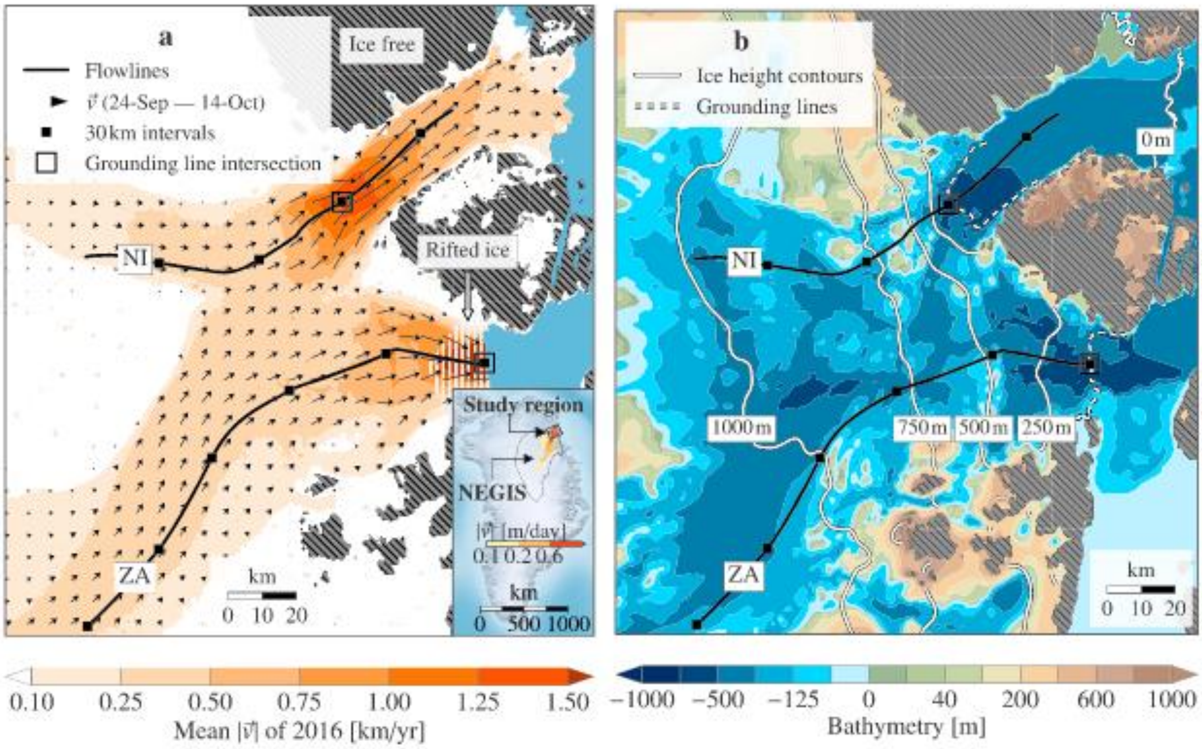

Figure 16 (Rathmann et al., 2017) Ice surface velocities (left) for 2016 showing flowlines, and bed/surface topography (right) of Zachariæ gacier (ZA) and 79N (NI) icestreams with2016 grounding lines (dashed white lines) and calving fronts. From Rathmann et al. 2017 , this shows the value in combining multiple CCI data sets (grounding lines, calving fronts and ice velocity) with model output, in this case daily modelled SMB from the HIRLAM/HIRHAM model system to elucidate key controls on the glacier system

Similarly Solgaard et al. 2018 focused on on Hagen glacier. and show that changes in the mass budget regime of outlet glaciers can be assessed based on changes to the velocity regime. They hypothesise that the change in surge type behaviour at Hagen Bræ in north east Greenland (see Figure 17 below) is in reponse to an increase in summer melt due to changes in basal hydrology.

Figure 1

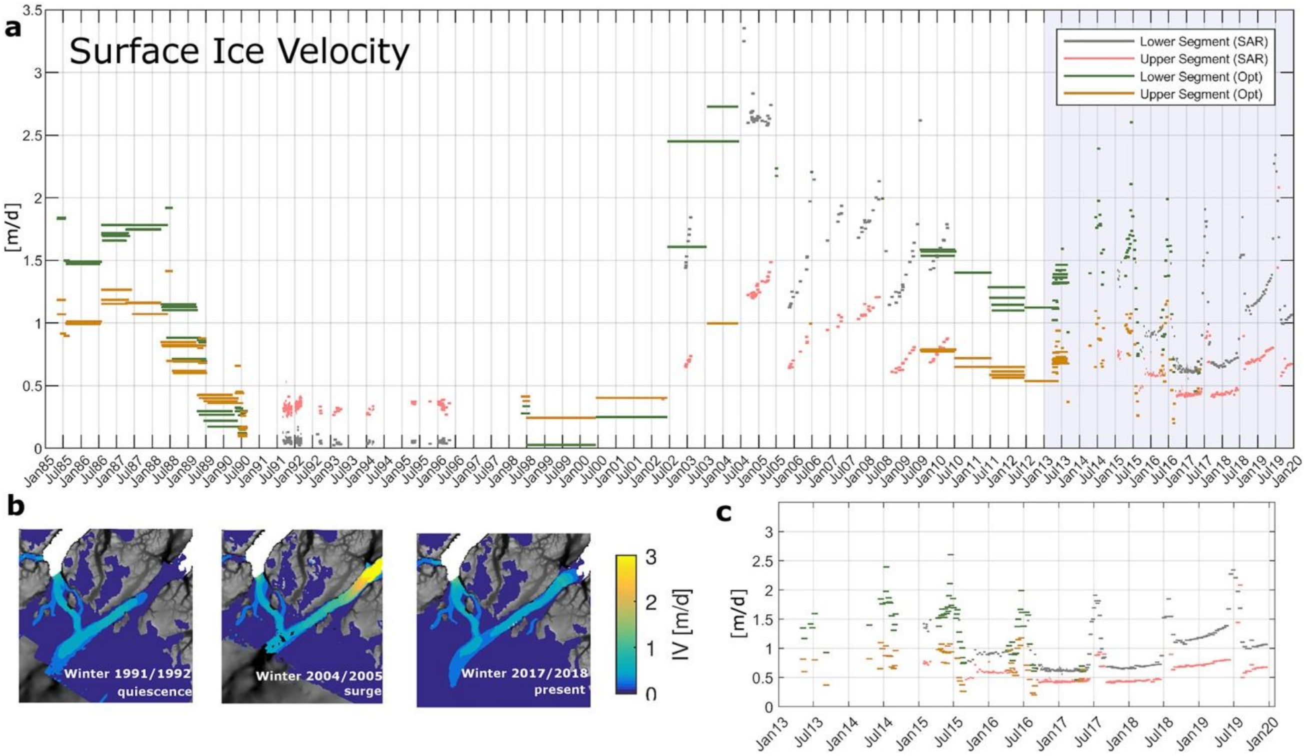

Figure 17 (Solgaard et al., 2020) (a) Ice velocity time series. The average velocity of the two flow line segments for each velocity map (for location see Figure 1a). The width of each bar shows the time span between the acquisitions. (b) Map plan view of the ice flow averaged over winter for three winters. (c) Zoom in on the shaded area in (a).

At a different glacier, Haubner et al., 2018 used IV data to assess output from the ISSM ice sheet model for the Upernavik Isstrøm region of NW Greenland. The frontal position of the model was constrained using observational data and this allowed an inversion technique to be applied to the model. Assessing the outcome of these simulations showed that in order to explain the observed velocities at this outlet glacier, the frontal position and the SMB forcing have to be well constrained, implying the importance of ice ocean and ice-bed interactions. These kind of insights are only gained when multiple data sets and models are combined to understand local conditions.

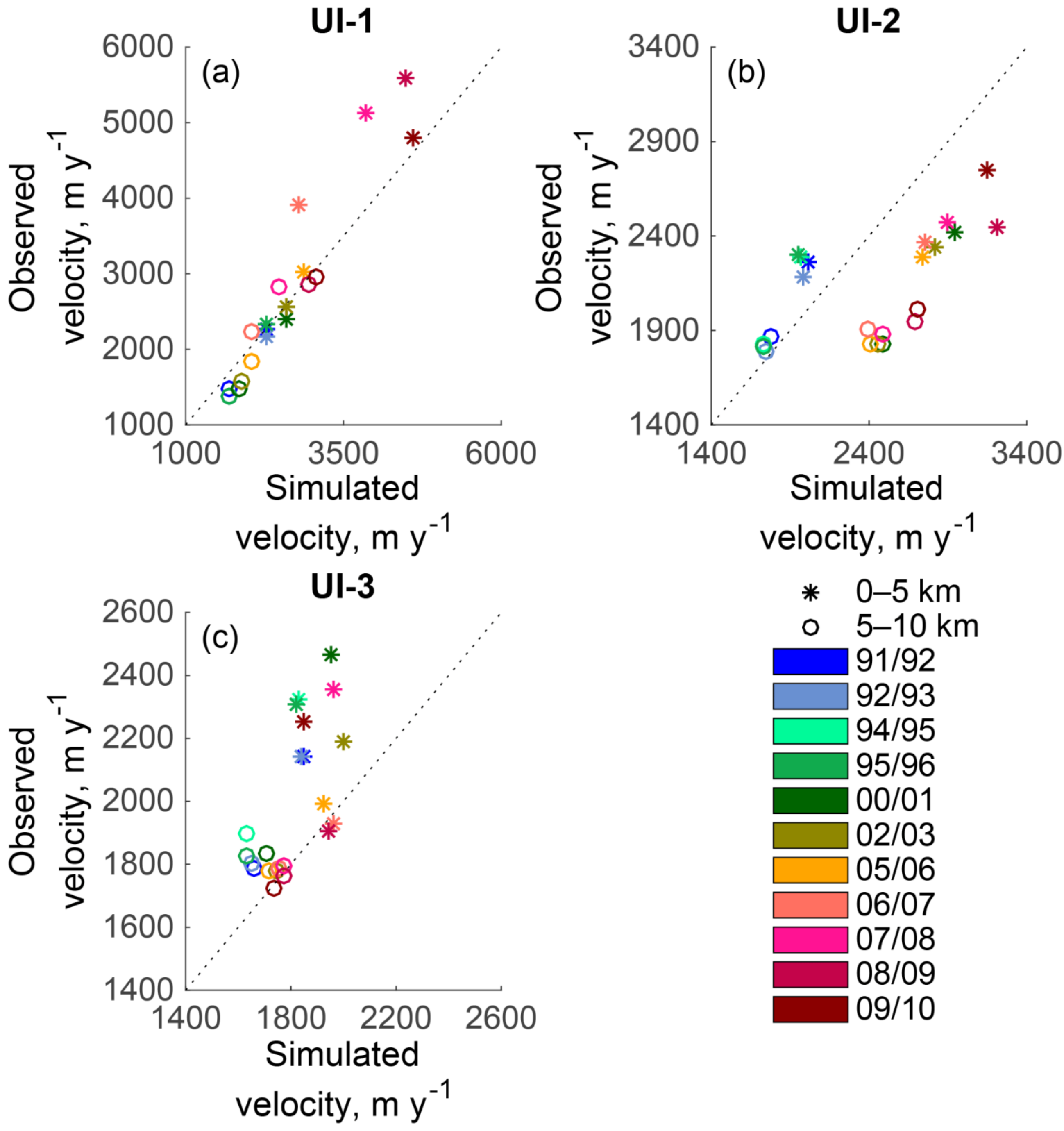

Figure 18 (Haubner et al., 2018) Observed vs. simulated ice surface velocity along the central flow lines of the three streams of Upernavik Isstrøm UI-1, UI-2 and UI-3. Stars mark mean velocity between 0 and 5 km from the 2012 terminus, dots refer to mean values 5–10 km upstream. Winter velocity maps for 1991/92,1992/93, 1994/95, 2002/03, 2005/06 and 2008/09 are produced from data available from http://esa-icesheets-greenland-cci.org/and described in Nagler et al. (2017). Winter velocity maps from 2000/01, 2007/08 and 2009/10 are given by MEaSUREs (Howat,2016)

On a larger scale, ice sheet wide inferences can be made with IV datasets. In particular, time series of ice-sheet-wide maps of IV are most valuable for determining impacts from changes in surface mass balance and temperature on the overall dynamics and flow of the ice. Obtaining a time series of the full dynamical state of the ice sheet is a truly valuable tool for determining the impact of changes in climate (surface mass balance and temperature) on ice sheet flow dynamics, making it possible to follow the response in over-all ice dynamics to changes in the climate signal. Solgaard et al, 2021 present a dataset along these lines, using also Sentinel data.

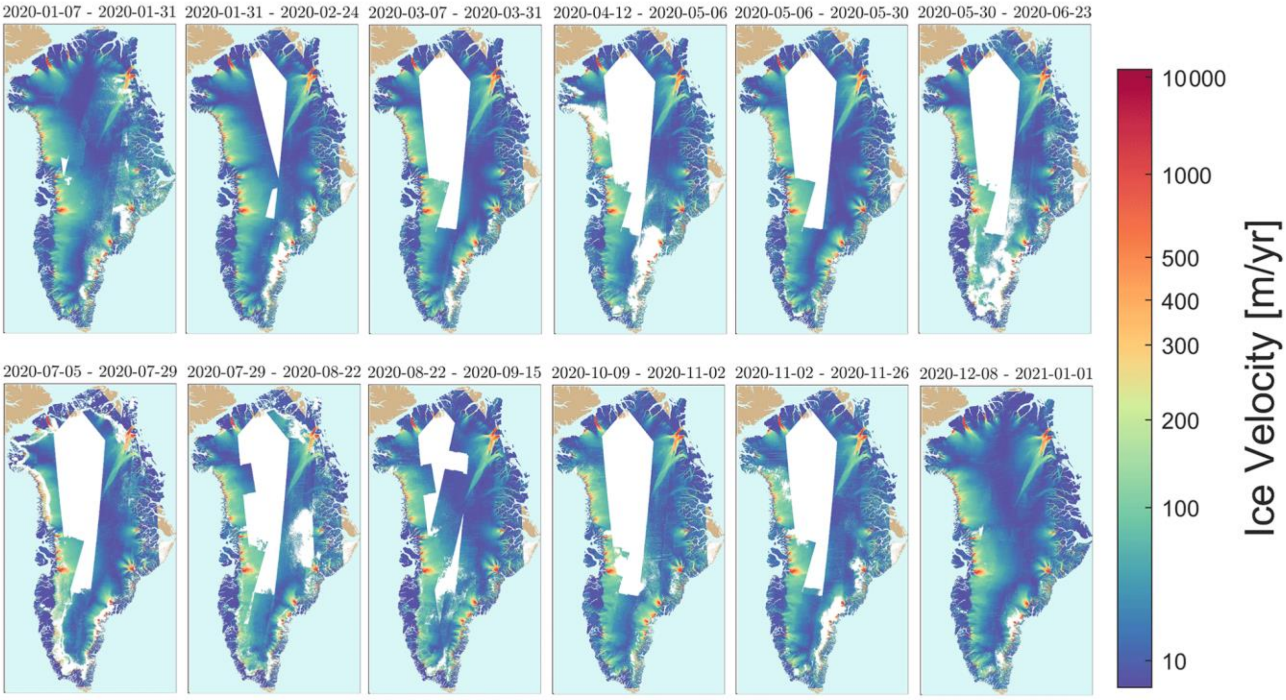

Figure 19 Examples of the Ice Velocity maps from 2020: from top left corner to lower right approximately one map per month over 2020 (Solgaard et al., 2020).

In terms of ice sheet model development this is an indispensable tool for validating and developing the flow dynamics of the models. Recent work by Aschwanden et al. (2016) demonstrated that very high model resolutions (<1km) are required in order to capture the complex Greenland outlet glacier flows, emphasizing the need for detailed observational data sets in model validation and development. Ice sheet models, both stand-alone and coupled versions, are most often driven either by annual or monthly means of surface mass balance and temperature and from that perspective a temporal resolution of the CCI data higher than the current ambition of an annual IV map should not take precedence over spatial coverage or duration of the time series, but for process studies higher temporal resolution where possible is useful (see Figure 19, Solgaard et al., 2020). The aim to have seasonal resolution of the key ice streams is also sufficient to resolve studies of the influence of melt water on flow velocities though evidence from Rathmann et al. (2018) of high variability on a timescale of days to weeks complicates this picture somewhat.

4.3 Calving front location CFL and grounding line location GLL

The representation of calving in large-scale ice sheet models is an area with significant room for improvement. Some models, such as PISM (Albrecht et al., 2012), have a calving scheme based on eigenvalues of the stress tensor (Albrecht et al., 2011, Winkelman et al., 2011), but this calving method is mostly valid for large, floating ice shelves and is, therefore, not applicable in the case of Greenland, where narrow and intricate fjord systems dominate the coast line. Other schemes are highly parameterised and relatively poorly tested (Pollard et al., 2015) or difficult to scale to large-scale 3-D ice sheet models (Åström et al., 2013). In the case of large-scale models of the Greenland ice sheet calving is often therefore represented by means of a calving mask determining an outer boundary for the ice. In the ISMIP6 model intercomparison, modelling groups were given a simple empirical parametrisation to use which, though fitted to existing data and simple to understand, is dissatisfying when applied to future projections without physical insight.

In ice sheet models, the location of the calving front is not usually an input parameter or model constraint (although the Haubner et al., 2018 study referenced above is a rare example of this). The location of the grounding line is determined from model dynamics and the bedrock topography. The CFL data is therefore not usually applicable as model input, but constitutes an indispensable data set for estimating model performance and model development.

The combination of the IV and the CFL (and GLL) time series makes it possible to perform studies of the impacts of changes in ice sheet flow dynamics on the advance or retreat of the CFL (and GLL), which, together with temperature and surface mass balance data can provide valuable insights to ice sheet dynamics and climate response. This is very well demonstrated in the study of Rathmann et al. (2018) shown in Figure 15 as well as the work of Hogg et al. (2016) on Petermann glacier. The grounding line changes identified in Hogg et al. (2016) are shown to be most likely a response to local tidal variability rather than realistic indicators of ice sheet dynamical changes, at least during the period up to 2011.

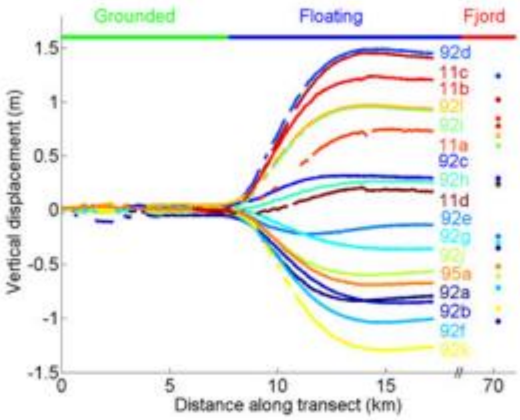

Figure 20 (Hogg et al., 2016) Relative vertical displacement along the transect E flow-line profile of the Petermann Glacier grounding zone, measured using 17 quadruple difference interferometry . Also shown (coloured dots) are relative tidal amplitudes at the same epoch as determined from the AODTM-5 model Arctic Ocean tide model. Between 0 and 8 km, there is no significant vertical displacement, indicating that this section of the glacier is grounded on bedrock. However, from 8 km and farther seaward, up to 1.5 m of relative displacement are recorded, indicating this section of the glacier is influenced by the ocean tide and therefore floating.

The spatial resolution of 250m is higher than the resolution of most ice sheet models, rendering the data sets quite suitable for comparisons and the temporal resolutions of the CFL and GLL products meet the needs of most model types, the seasonal resolution of the CFL making it a very useful product for studies of seasonal influences on calving rates. Together with the wealth of data becoming available from the Oceans Melting Greenland (OMG) project (Fentyet al.,2016), the CFL and GLL data products are valuable contributions to scientists working on understanding the dynamics controlling calving outlet glaciers in Greenland (e.g. Muenchow et al., 2016). Their importance was highlighted in a review article by Friedl et al (2020) (see figure 19) who note “The precise positioning and long-term monitoring of the grounding line, forming the boundary between grounded and floating ice of marine ice sheets and tidewater glaciers, is critical for assessing ice sheet/glacier stability, ice sheet/glacier mass balance calculations and numerical ice modelling”.

Although updates within the CCI are now discontinued, their value of when combined is amply demonstrated by a project currently underway where strain rates derived from IV using a velocity gradient approach are used to drive a fracture model of Petermann Glacier. The ice fracture model is being used to determine rates of calving and evaluated against the calving front position product. In combination with modelled melt, the velocity shows a strong relationship to melt production (Rosier et al., in preparation).

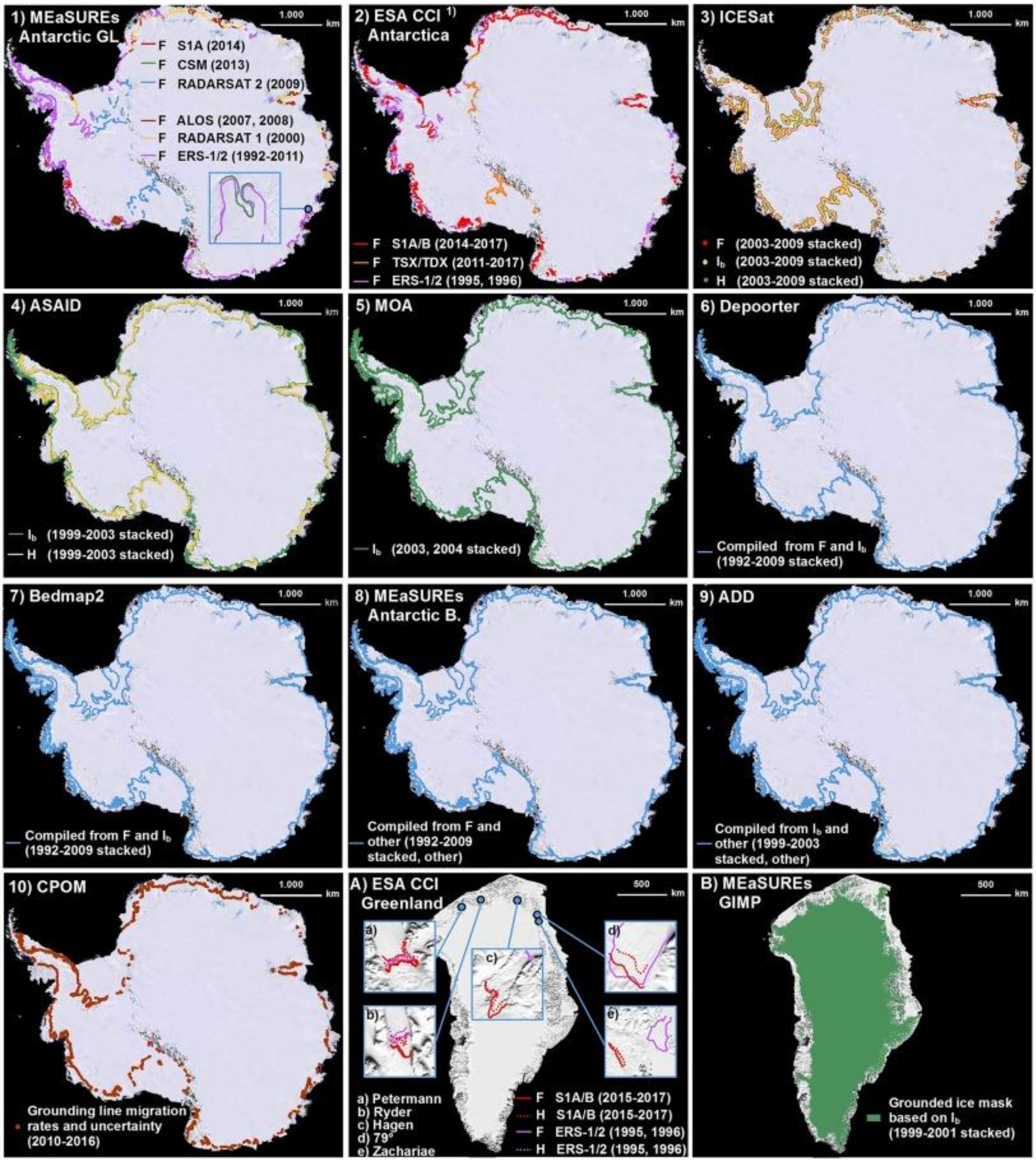

Figure 21 taken from Friedl et al., 2020 Spatial and temporal coverage of freely available grounding line datasets. Abbreviations: Sentinel-1 (S1), COSMO-SkyMed (CSM), ALOS PALSAR (ALOS), TerraSAR-X/TanDEM-X (TSX/TDX). Basemaps: USGS LIMA (U.S. Geological Survey, 2007) and MEaSUREs MODIS Mosaic of Greenland (MOG) 2015 (Haran et al., 2018).

4.5 MFID

The newly established MFID data product has been an enormously valuable addition to the monitoring of the Greenland ice sheet. The monthly update has allowed the near real time assessment of ice sheet evolution in addition to SMB monitoring calculated using weather output. Significant results reported by among others (Mankoff et al., 2019) show that although the contribution of fast-flowing ice (see Figure 20 below) has remained high, the relative contribution of different basins has changed.

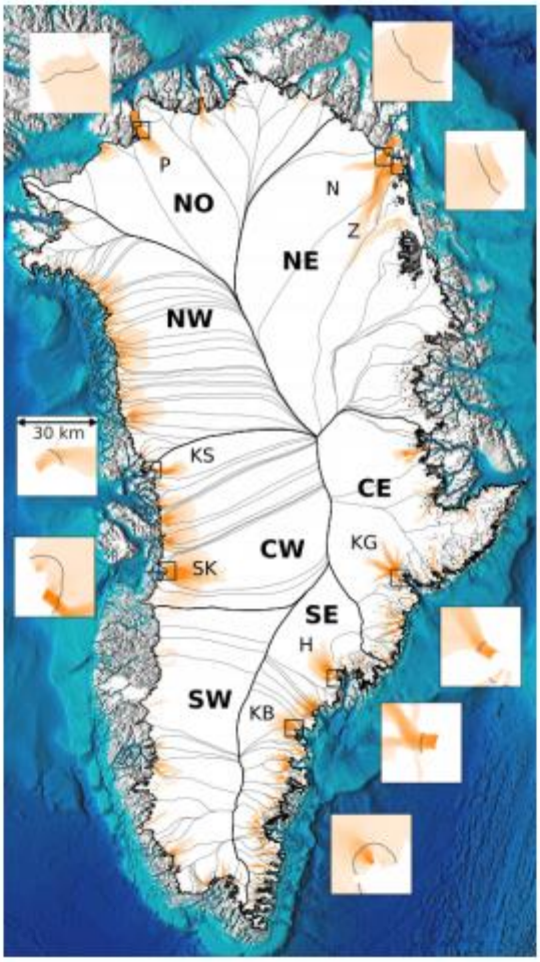

Figure 22 (Mankoff et al., 2019) Greenland ice sheet drainage basins showing fast-flowing ice (orange, greater than 100 m yr−1) and the flux gates for the top eight discharging glaciers shown in Figure 18 below.

Among the trends that Mankoff et al. (2019) identify is a marked reduction in the discharge from Sermeq Kujalleq (also identified by (Khazendar et al., 2019) but compensated for by an increase in ice discharge from Helheim glacier (see Figure 19 below).

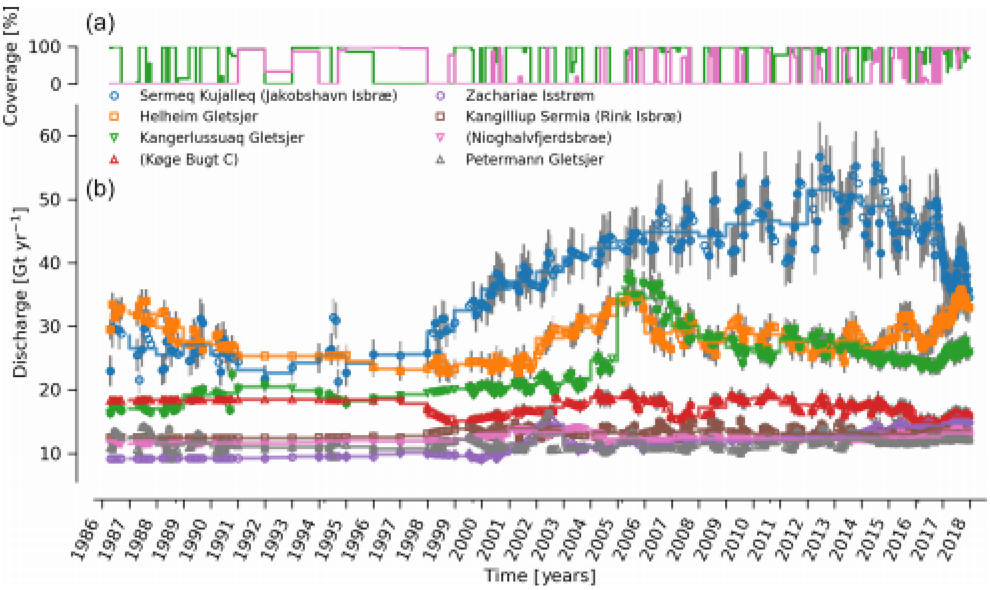

Figure 23 (Mankoff et al., 2019) Time series of ice discharge showing the top eight discharging outlet glaciers

The regional trend in ice discharge is a valuable one as it pinpoints regions where process studies can best be focussed in understanding the drivers of that variability.

3.6 Gravitational Mass Balance

The GRACE-derived gravitational mass balance (GMB) is presented on several websites and publications (e.g. www.polarportal.dk) and has proven to be a timely and useful dataset, not just for overall Greenland trends, but also for month-to-month studies and evaluation of climate models (e.g. Price et al., 2017) and the associated modeled ice sheet melt or mass gain through snow accumulation.

Although GRACE at the moment is only capable of resolving anomalies on the scale of hundreds of km, it is useful to quantify *where* action is taking place, e.g. on the east, west or northern coastal regions (see figure 20 below), and climate change effects can also be followed very nicely when monthly solutions are animated into movies of accumulating mass loss.

In a recent study, (Fettweis et al., 2020) GMB data was combined with a selection of output from Surface Mass Budget models on a regional scale and used to determine the likely biases (see Figure 20). By combining SMB and MFID data, the analysis shows on a regional scale where there are likely biases in SMB model solutions.

The regional component is important in this case as the overall ice sheet mass budget shows better performance than many of the individual basins, suggesting that there are compensating errors in the SMB solutions from different models. This analysis also gives us a means of assessing how individual models perform compared to the ensemble and where sources of error are likely to be.

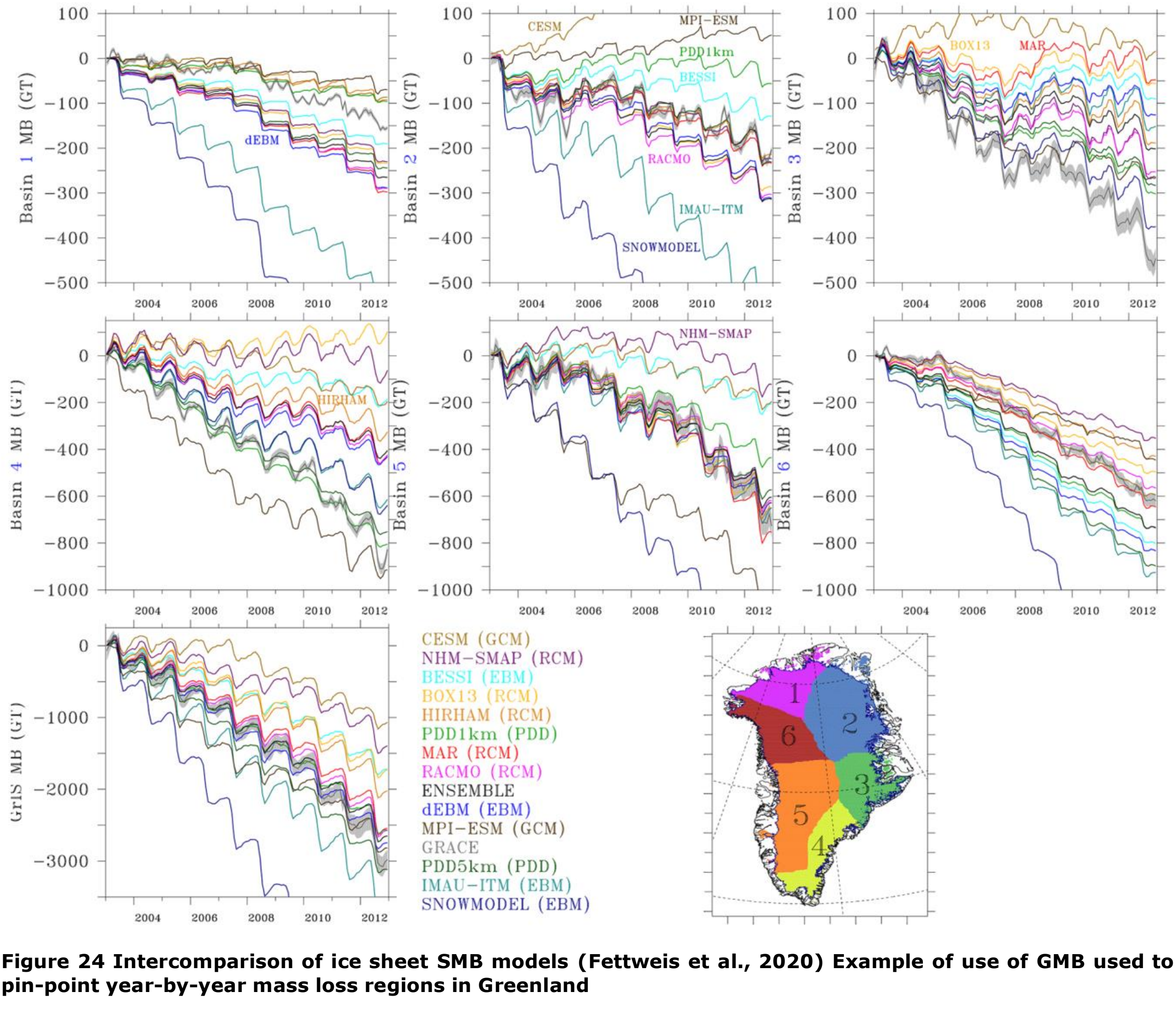

Figure 24 Intercomparison of ice sheet SMB models (Fettweis et al., 2020) Example of use of GMB used to pin-point year-by-year mass loss regions in Greenland

While Fettweis et al (2020) look at the SMB models and use GMB and discharge to assess their performance, it is also possible to use a similar technique and look at time series of mass change as shown in Figure 22 (Mottram et al., 2019).

A surprising finding has been looking in detail at the basin resolved GMB data in comparison with similar basins from the SMB. The comparison with the GMB data at an ice sheet level shows an as expected seasonally resolved cycle with SMB values mostly higher than GMB. However, at the basin scale this breaks down with significant interannual variability as well, suggesting that either the models are overestimating precipitation or that there are some surprising ice dynamics or some combination of the two.

Interestingly both RACMO and HIRHAM (Figure 2020) regional climate models show a very similar pattern suggesting that there may be issues of systematic bias in climate models, see for example basin 4.

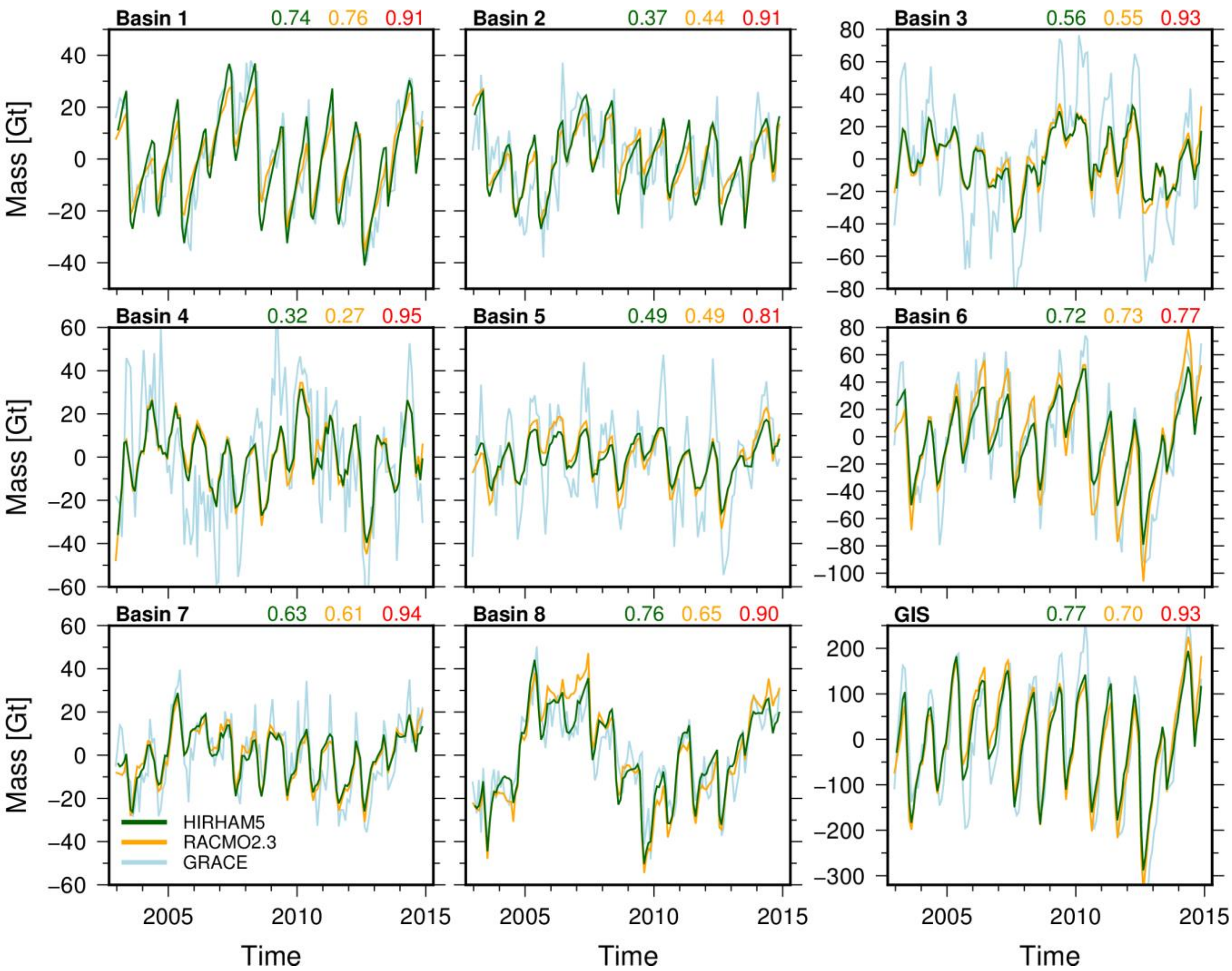

Figure 25 ((Mottram et al., 2019) GRACE GMB and SMB from RACMO and HIRHAM5 shown on a basin scale (Groh, personal communication)- Large seasonal and interannual variations are shown in all three datasets. Curves have been smoothed with a quadratic function to assist interpretation.

4.4 Use of ECVs in ice sheet and climate models

In model systems where the ice sheet is not actively coupled to the atmospheric and/or oceanic components but enters as a passive element, an observed state of the ice sheet may be used directly as the reference ice sheet seen by e.g. the atmosphere. For such purposes, detailed, high-resolution data sets of ice sheet characteristics such as SEC, CFL and GLL are very useful as Aschwanden et al. (2013) and Price et al. (2017) have shown. As model resolution increases, the accuracy of topographic features of the ice sheet becomes progressively more important. Studies with very high resolution runs using a regional climate model show significant changes in precipitations patterns over Greenland when the resolution increases (Lucas-Picher et al., 2012). In such high-resolution runs detailed, high-resolution data sets of ice sheet topography and extent are essential for optimal model performance, a model study currently in preparation by Mottram et al (in prep.), examines exactly this feedback (see Figure 24 below).

When the ice sheet is not actively coupled to the components of a regional climate model, time series of ice sheet variables relating to the ice sheet topography and extent such as SEC, CFL, GLL and GMB may be fed into the model at appropriate intervals throughout a historical run, thereby allowing the regional climate model to respond to any changes in the ice sheet. Such historical runs usually driven by some form of reanalysis data are typically used to validate and test model performance or as part of the spin-up process of the regional climate model prior to projection runs. Providing observed ice sheet parameters for such runs rather than fixed, prescribed values would be very useful in terms of optimizing model performance. Exactly this procedure is envisaged for possible use in the CARRA reanalysis project (see section 3.2) where the high resolution reanalysis can use the annually produced SEC to provide a refined high resolution surface topography which will likely improve the modelled near surface climate in the reanalysis product.

The importance of accurate surface topography and taking into account these processes is demonstrated in figure 24 where experiments in the HIRHAM5 regional climate model were carried out with modified topography (Mottram et al., in prep).

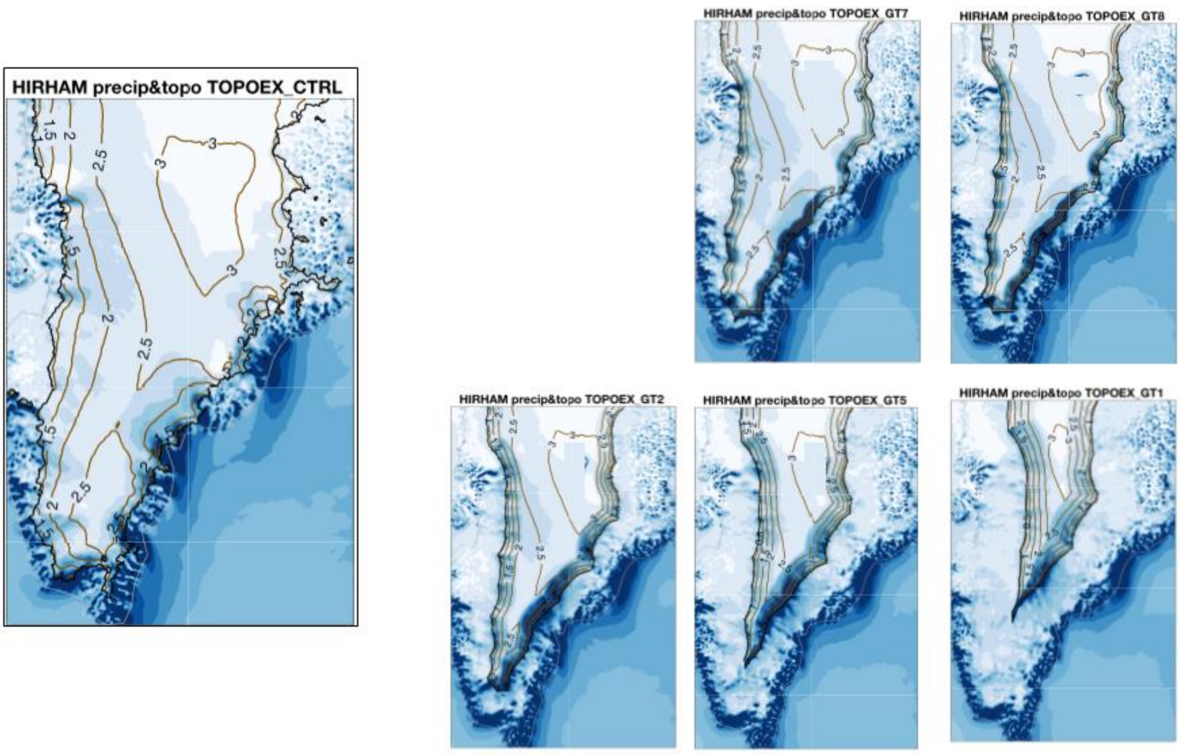

Figure 26 Ice sheet topography experiments illustrating the importance of topography to precipitation compared with a reference (far left) topography (Mottram et al., in prep).

Coupled ice-sheet-atmosphere-ocean models the evolution of the ice sheet is determined by the forcings stemming from the atmospheric and oceanic components of the model and no external driving data for the ice sheet is needed over the scenario run. However, the quality of the initial representation of the ice sheet in a coupled model system is essential (Price et al., 2017; Aschwanden et al., 2013). In this case, the initial state must meet a double set of criteria, one being compliance with observations, the other being thermal equilibrium between the ice sheet and the mean climate of the model system (Adalgeirsdottir et al., 2014). Prior to scenario runs, spinup runs need to take place in order to produce ice sheet initial states that contain long-term memory of their past evolution and are self-consistent with respect to the climate forcing, ice temperature, ice thickness and velocity (Goelzer et al, 2013). The spinup state as well as the method applied for the spinup itself has been shown to affect the ice sheet model response (Aschwanden et al., 2013, Aðalgeirsdóttir et al., 2014) and high-quality observational data sets validating the final post-spinup ice sheet states that serve as initial states for projection runs are in great demand (Price et al., 2017).

There is also interest and need for time series that are as long as possible and without gaps. In the case of the coupled EC-Earth-PISM system, an upgraded system with a T255/L91 resolution for the atmospheric part and 5km resolution for the ice sheet is currently under development (Madsen et al., submitted). Such a system produces approximately 45GB per model year with 6-hourly output, but around 170GB per model year if enough fields are saved in order to be able to derive the necessary forcing fields for regional climate models. This model system along with several other climate and ice sheet models is part of the planned CMIP6 (Climate Model Intercomparison Project) as well as the ISMIP6 (Ice Sheet Model Intercomparison Project for CMIP6), (Eyring et al., 2015; Nowicki et al., 2016). This large intercomparison study provides valuable insights to the climate and ice sheet modelling communities and pushes the current standards for model capability. The existing ISMIP6 and proposed ISMIP7 do not yet take full advantage of the CCI data products that could be an important tool for model evaluation and initialisation, and we suggest a more active effort to collaborate with the ISMIP6 steering group by e.g. inviting them to join the climate research group will be valuable when undertaking the effort. High-resolution datasets of SEC, IV, MFID, GLL, CFL and

GMB can serve as valuable constraints, initial states and benchmarks for both coupled and stand-alone ice sheet models.

In the case of stand-alone ice sheet models, resolutions are generally increased compared to the coupled model systems. This increase in model resolution alone results in better ice flow dynamics since an increase in resolution enables a much more detailed bedrock topography, particularly considering the glacial outlets around the margin. Also, the forcing fields driving the models may come from regional climate models running at much higher resolution than a global climate model, thereby providing more accurate fields of SMB, temperature and precipitation to drive the ice sheet model. Most regional climate models run on resolutions around 10 km, with studies showing the benefits of going of surface mass balance calculations at even higher resolutions either dynamically (Lucas-Picher et al., 2012) or statistically (Noël et al., 2016). Improvements are found particularly in the distribution of precipitation, in areas of steep topography, nonetheless, evidence from Hermann et al., (2018) suggests that even higher resolution, likely non-hydrostatic models with sophisticated cloud microphysical schemes will be needed to be able to simulate surface mass balance fields adequately for high resolution (higher than 5km) ice sheet modelling. Running an ice sheet model at 20km resolution compared to 5km resolution with a corresponding increase in the resolution of the driving climate model will have a significant impact on the flow field.

The value of the ECVs increases with temporal coverage and continuity of the data products. For regular validation purposes with ice sheet models, it is usually necessary to have decadal scale coverage. Even then, validation can be difficult as some ice sheet models might run through several ice age cycles before reaching the satellite era. Yet, an increasing amount of diverse model validation data is becoming available, such as a comprehensive mapping of the internal layers (isochrones) of the ice sheet derived from airborne ice-penetrating radar (MacGregor et al. 2015) to supplement the GIS_cci ECVs, adding to the possible constraints which can be imposed on a given ice sheet model. ECVs such as CFL and GLL are currently useful for simple correlation analysis with possible climatic forcing parameters to identify first-order ice-ocean interaction mechanisms, but are also crucial for more advanced attempts at transient model inversion where boundary conditions must be imposed at every time step during the modelled period. Transient inverse modelling is in development for the most advanced current ice sheet models and has already produced impressive results used in the development of ESA CCI products (Bindschadler et al., 2013; Morlighem et al., 2014), stressing the need for these ECVs. Direct (non-transient) inversion of e.g. basal friction using a single field of IV and SEC is already well-developed and the GIS_cci ECVs are currently being used for this purpose (e.g. Larsen et al., 2014).

5 Summary

5.1 Outreach and Communication

A key part of the work of the CCI has been in spreading the datasets and encouraging their adoption into the scientific community. As this report shows, there has been a substantial effort and rewarding amount of studies produced that rely in whole or in part on the GIS_CCI datasets.

The use of the datasets on the Danish Polar Portal website has also helped to promote the use of CCI products in the scientific community. Perhaps more importantly, the visualisations have also helped to communicate major findings as well as better understanding of the processes important for the Greenland ice sheet to the general public as well as promoting these and associated data products to journalists and stakeholders such as planners, politicians and decision-makers.

However, a somewhat overlooked segment up to now, has been users of CCI datasets within Greenland. The launch of the QGreenland open source GIS tool now gives us better potential to reach these stakeholders as it incorporates, along with a great deal of other datasets, CCI data. The QGreenland tool itself is based on the freely available QGIS software and provides a mapping tool as well as meta data for abundant datasets. Examples are shown in Figure 27 below.

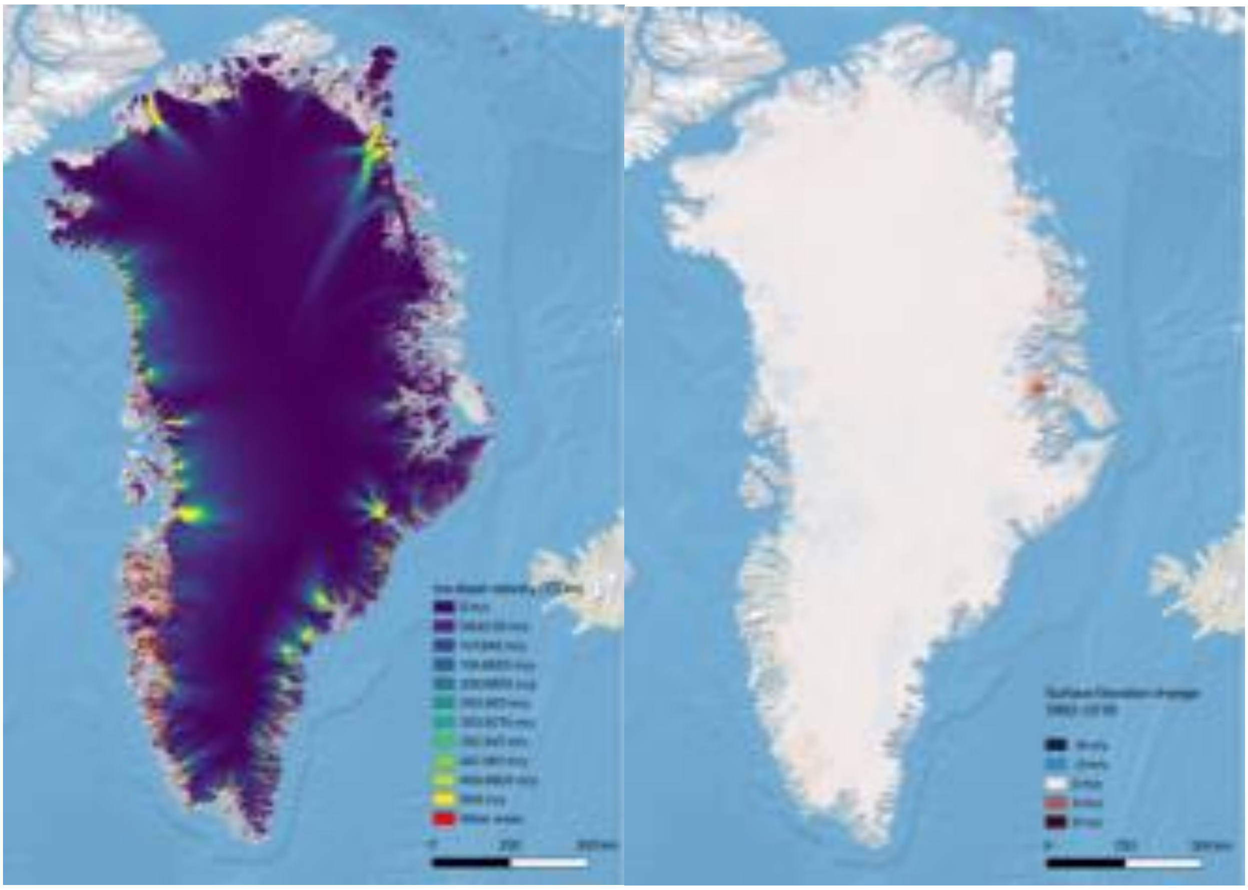

Figure 27 Example maps produced from QGreenland showing IV (left) and SEC (right)

The inclusion of CCI_GIS data in QGreenland is important as it is expected to become a major tool for scientists and policymakers in many different areas to access Greenland data.

5.2 Potential additional datasets in the project

In the long term, should further extensions of the project be planned, the addition of albedo data to the existing suite of variables would be very valuable to the climate model community. In a coupled climate model all model components evolve freely, driven by the radiative forcing alone to calculate surface mass balance (and, possibly, an oceanic forcing based on ocean temperatures). Albedo is a major source of uncertainty in SMB, particularly when it comes to bare glacier ice. In most climate models, the current albedo parameterizations over ice and snow surfaces are rudimentary, and major efforts are put into improving these albedo parameterizations and surface schemes. Recent work with the HIRHAM model shows a pronounced difference in model performance between model runs using the model's albedo parameterization over the Greenland ice sheet compared to runs using satellite-based albedo measurements over the Greenland ice sheet with the models runs using measurement-based albedos showing the best performance (Langen et al., 2017). The need for better albedo parameterizations of the ice sheet is obvious, and a CCI albedo product would be an indispensable asset in coming and ongoing projects on development of albedo parameterizations in climate models. Such a data project would also be useful for coming iterations of climate reanalysis in the Arctic.

Other datasets that could be considered include ice thickness, as this is crucial to estimates of MFID and for evaluating the performance of ice sheet models and accumulation derived from SEC or other datasets (e.g. GNSS, radar) an essential and hard to measure variable on the ground.

More important however, is maintaining and keeping updated existing datasets within the CCI project. The inclusion of some of these data in for example the recently released Copernicus Arctic Regional ReAnalysis (CARRA) to assess ice sheet topographic and extent changes shows that the continuation is important for improving climate and weather models.

5.3 Recommendations

The GIS_cci project has successfully improved and extended the existing data sets produced during CCI phase 1, 2 and CCI+ along with the introduction of additional ECVs. Similarly, the use of GIS_CCI data by the scientific community is increasing, along with the number of downloads as shown by the selected case studies described here. There are likely many more that we as a CRG are unaware of or that have yet to be published. We have also identified in the text a number of opportunities for further research that the application of ECVs will certainly assist in. There are doubtless others beyond the range of our expertise and imagination.

- While spatial resolution is ever improving in models and should be considered as the project continues, improving the length of the time series rather than increasing temporal resolutions is desirable within the framework of coupled ice-sheet-climate models given the time scales of the problem and the response times of the ice sheet to changes in the climatic forcing. Longer time series improve statistics and confidence in the results.
- The need for an increase in spatial resolution within the ECVs is debatable and depends very much on the type of study; in the case of coupled ice-sheet-climate models, an increase in spatial resolution is not particularly important given the typical grid resolutions of the models. However, finer resolutions are of interest for more specific process studies and for offline models and single-basin modelling such as, e.g. inversion studies and various studies relating to melt water and exploitation potentials regarding hydropower. Overall, as kilometre scale ice sheet models become more common it is desirable that especially SEC and IV also become more highly resolved, but only where data quality permits.
- We recommend further engagement with a number of projects and consortia where the use of this data could be immensely helpful to better defining uncertainties and improving process understanding of key parts of the cryosphere system. To this end the involvement of GIS_CCI in the Horizon Europe projects on sea level rise is certainly beneficial. Other relevant Horizon 2020/Europe consortia who are already engaging with the GIS_CCI project or intend to in future include the polar processes regional climate project PolarRES and the climate tipping points project TIPES.
- The climate research group can play a role in both scientific research based on ECVs and in pushing the application of the ESA_CCI Greenland datasets to current scientific problems. There has been significant interest from various media companies in producing wildlife and climate themed documentaries, these could undoubtedly be enhanced with work in collaboration with the ESA climate office
- The wide range of case studies, process studies and mass budget assessments displayed here are in many ways only scratching the surface of what could be done with the CCI ECVs. The accessibility of the datasets combined with the relatively long time-series and ever increasing advances in climate and ice sheet modelling means that the GIS_CCI ECVS present a very good opportunity to involve students and other early career scientists in their exploitation. Such use could take the form of either a long MSc type project or a summer school/hackathon/bootcamp type project where over the course of a week or two students work on defined short projects assisted by a senior scientist mentor. These have been very successful in other contexts (for example, the ECMWF Summer of Code, and the IceSat-2 hackathon weeks) in producing short, user driven examinations of particular datasets. These could also include the development of data visualisations, operational monitoring products and public outreach as well as more scientifically oriented process studies. Collaboration

with other CCI projects including but not limited to Antarctica, Sea ice, land surface temperature and snow would likely enhance results and widen participation,

- The participation of GIS_CCI in the IMBIE intercomparison proves the value of community intercomparisons to assess the current state of the ice sheet. Continuing participation is essential to maintain the relevance of the project but also as a valuable and consistent data set. Other similar community projects that could usefully include GIS_CCI ECVs include the ISMIP6 (Ice Sheet Model Intercomparison Project for CMIP6) and the CORDEX (Co-Ordinated Regional Dowscaling Experiments) as well as OBS4MIP should be encouraged (via the climate research group) is likely to deliver benefits for both groups.
- Extending the use of GIS_CCI data to experiments assessing the place of Greenland ice in the earth system is an important and still somewhat unexplored avenue of research. The possibility of tipping points in the earth system being exceeded, including effects of run-off on north Atlantic overturning circulation and changes in atmospheric circulation are still uncertain and potentially high impact events. These are still questions at the frontier of research for which GIS_CCI data can contribute.
- The Climate Research Group was unfortunately reduced with the tragic loss of Konnie Steffen in an accident at Swiss Camp in 2020. The establishment and revision of a new CRG to include a mix of both established and early career scientists at a range of institutes able to work in line with some of the recommendations of this report will help to disseminate and develop the outputs further in the future
- Public outreach and communication remains an important part of the CCI_GIS project and should use existing channels to facilitate this, not only when important results are delivered but also for example via the QGreenland interface and on the polar portal website as well as via ESA climate stories. Developing visualisations based on e.g. MFID or IV would be an obvious next step for example.

Proposed case studies for the next phase:

1. The use of IV, CFL and SEC to understand the role of ice mélange (sikussaq) in affecting calving retreat of Greenlandic outlet glaciers
2. Copernicus Arctic Regional Reanalysis gives a new ultra high resolution climate data set that can be used to understand observed changes in the Greenland ice sheet and in preparation for the new CARRA which will be pan-Arctic
3. As climate models are run at higher and higher resolutions, the role of surface lakes in affecting the surface energy budget will start to become important in estimates of ice sheet mass budget. In addition the role of lake drainage in moderating the dynamics of ice flow of the Greenland ice sheet is an interesting and still unsolved problem. A case-study combining SGL and IV together with climate reanalysis and climate models to examine how to parameterize lakes into climate models as they become more widespread over the ice sheet surface as well as applications in ice sheet mass budget analysis.
4. The systematic use of the IV dataset to evaluate and tune these models will prove helpful in parameter sensitivity studies (e.g. Aschwanden et al., 2019, 2022), reaching out to the ISM community, for example via the Horizon 2020 project PROTECT to ensure the data is provided in an easy to use format will help to improve models given the identified problems that existing ice sheet models exhibit in simulating ice sheet dynamics.

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