ESA Climate Change Initiative (CCI)

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

Climate Assessment Report (CAR)

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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 at end of section Updated figure 2.4 on data product traffic per Q3 2018	Released to ESA 2018-10-26

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 a final and 3rd update on the Climate Assessment Report (CAR), summarising the work carried out over Phase 2 of the "Greenland_Ice_Sheet_cci" (GIS_cci) project in accordance with the Contract [AD1] and Statement of Work [AD2].

This final CAR is, like the predecessor climate assessment reports (CAR for Year 1 and Year 2) it is based on, part of Task 5 Climate Assessment Systems Evolution 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 aims to give an update on the uses of the Greenland ice sheet data by the scientific community and focuses in particular on published or soon-to-be-published analysis. We also identify opportunities for further analysis and engagement with other scientists within international science collaborations as well as outreach to the public.

There are five parts:

- Use to the climate research community;
- Data integration into climate models;
- Implementation of ECVs in models;
- Usefulness of the GIS_cci products;
- Recommendations.

1.2 Background

The response of the Greenland Ice Sheet to current and future climate change is a matter of great concern and interest, 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 and uncertainties around the ice sheet response to climate change are a key uncertainty in the recent IPCC 5th Assessment Report (Vaughan et al., 2013). In support of reducing uncertainty and enhancing process understanding, the best possible validation data as well as reference data sets that may serve as boundary conditions and constraints are in great demand. This demand is also driven in part by the IPCC special report focusing on oceans and the cryosphere as well as the ongoing sixth climate model intercomparison exercise (CMIP6), for which the role of ice sheets in the climate system is a particular area of focus (ISMIP6).

The GIS_cci Climate Research Group (CRG) has assessed the applicability of the GIS_cci products and within this document we show a few examples of where the ECVs have already been applied in scientific projects. As the data has not been available for a period equivalent to the full cycle of a published academic article, we expect many more scientific publications to result from or benefit from the CCI dataset. The high visibility of the CCI was on display at the Polar 2018 open science conference where several consortium members made presentations and where many other participants showed scientific results predicated on CCI Greenland and/or Antarctica.

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. 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 should be more specifically targeted as likely users of the ESA_CCI data products.

We would also like to note that the use of the data to produce graphics and gifs 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.

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 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	ESA/Contract No. 4000112228/15/I-NB, and its Appendix 1	Phase 2 of the ESA Climate Change Initiative, Greenland_Ice Sheet_cci	2015.04.14	-
AD2	CCI-PRGM-EOPS-SW-12-0012 Appendix 2 to contract.	Climate Change Initiative – SoW Phase 2	2014.06.11	Issue 1 Revision 3
AD3	CCI-PRGM-EOPS-TN-12-0031	CCI System Requirements	2013.06.13	Version 1
AD4	CCI-PRGM-EOPS-TN-13-0009	Data Standards Requirements for CCI Data Producers	2013.05.24	Version 1.1

Table 1.2: List of Reference Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
RD1	ESRIN/Contract No. 4000104815/11/I-NB	Phase 1 of the ESA Climate Change Initiative, Ice_Sheets_cci	2012.02.	
RD2	ST-DTU-ESA-ISCCI-CAR-001	Climate Assessment Report (CAR), for Phase 1	2015.09.28	2.1
RD3	ST-DTU-ESA-GISCCI-URD-001	User Requirement Document (URD)		
RD4	ST-DTU-ESA-GISCCI-PSD-001	Product Specification Document (PSD)		
RD5	ST-DTU-ESA-GISCCI-DARD-001	Data Access Requirement Document (DARD)		
RD6	ST-DTU-ESA-GISCCI-ATBD-001	Algorithm Theoretical Baseline Document (ATBD)		
RD6	ST-DTU-ESA-GISCCI-ATBD-002	Algorithm Theoretical Baseline Document (ATBD), Round Robin Exercise		
RD8	ST-DTU-ESA-GISCCI-CECR-001	Comprehensive Error Characterisation Report (CECR)		
RD9	ST-DTU-ESA-GISCCI-DARD-001	Data Access Requirement Document (DARD)		
RD10	ST-DTU-ESA-GISCCI-SSD-001	System Specification Document (SSD)		
RD11	ST-DTU-ESA-GISCCI-SVR-001	System Verification Report (SVR)		
RD11	ST-DTU-ESA-GISCCI-PUG-001	Product User Guide (PUG)		
RD12	ST-DTU-ESA-GISCCI-PVIR-001	Product Validation and Inter-comparison Report (PVIR)		
RD13	ST-DTU-ESA-GISCCI-CAR-001	Climate Assessment Report (CAR)		

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

Special references used for this document during Phase 1:

1. **[PSD] L. Sørensen et. al**., Product Specification Document for the Ice_Sheets_cci project of ESA's Climate Change Initiative, version 1.2, Aug. 2012.
2. **[DARD] A. Shepherd, et al.**, Data Access Requirements Document for the Ice_Sheets_cci project of ESA's Climate Change Initiative, version 1.7.6, 09 October 2012.
3. **[PVP] T. Nagler, et al.**, Product Validation Plan for the Ice_Sheets_cci project of ESA's Climate Change Initiative, version 1.2.1, 21 Aug. 2012.
4. **[ATBD] K. Scharrer, et al.**, Algorithm Theoretical Baseline Document for the Ice_Sheets_cci project of ESA's Climate Change Initiative, version 0.8.1, 09 October 2012.
5. **[PVASR] K. Scharrer, et. al.**, Product Validation and Algorithm Selection Report for the Ice_Sheets_cci project of ESA's Climate Change Initiative, version 0.6.1, 06 November 2012.
6. **[URD] Hvidberg, C.S., et al.**, User Requirements Document for the Ice_Sheets_cci project of ESA's Climate Change Initiative, version 1.5, 03 Aug 2012.
7. **[PVIR] Langer, M. et al.**, Product Validation and Intercomparison Report, version 1.3, April 2015.

2 Usefulness to the climate research community

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 produces a number of ECVs (SEC, IV, GLL, CFL and GMB), all of which are of great relevance to the very diverse range of scientific fields and approaches that constitutes the climate research community.

For the purposes of this report we use the following abbreviations:

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

From an observational point of view, the 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; as just a few examples, Sørensen et al. (2011) 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 both SEC and IV. ECVs like SEC and IV have 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. The 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., in preparation; Rosier et al., in preparation) or have not been documented in different parts of Greenland.

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, where 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 have recently 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). 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). 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) show spatially dense observations are the preferred metrics for the use of hindcasting in order to assess modelled rates of change.

We suggest that the ISMIP6 modelling exercise (Ice Sheet Model Intercomparison Project for CMIP6) 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). Similarly, an overview of the ESA-CCI dataset integrated with ice sheet and climate model data currently in preparation (Mottram et al., in prep., expected submission data 30th June) is likely to be of great assistance in summarising recent ice sheet trends and changes for the IPCC Special Report on Oceans and the Cryosphere. This review article of the Greenland Ice Sheet CCI should be read as an annex to the CAR.

2.1 Deriving mass balance from ECVs

The SEC is of specific importance to the mass balance derivation. However, it is far from trivial to derive mass change from SEC due to firn compaction, signal penetration, difficulties over sloping surfaces or variable topography and shortcomings in spatial coverage. This central challenge is being addressed by scientists in the IS-CCI (Sørensen et al., 2015; Levinsen et al., 2015) and SEC interpretation in terms of mass change is improving. 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.

The new GMB (Gravimetric Mass Balance) product fills an important niche in the assembly of the Greenland Ice Sheet ECV's, 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 major 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, and an integral measure to which the other techniques (SEC derived and Input-Output method mass balance estimates) will ultimately have to agree with. This therefore also underpins the necessity of the recent IMBIE and planned IMBIE2 method intercomparison activities.

The scientific usefulness of GRACE data is highlighted in the running of coupled climate-glaciological models for the modeling of overall ice sheet mass balance. Such an example is shown in Fig. 2.1, where an integrated ice sheet model, forced by a regional, globally consistent meteorological model (DMI HIRHAM), clearly shows that the long-term trend in the Greenland Ice Sheet mass loss is underestimated by such models. This is likely due to lack of sufficient modeling of long-term dynamic effects, whereas short term changes are extremely well-modelled. Apart from ice dynamics, the accuracy of the surface mass balance fields driving the model is essential. These fields are determined from climate models, where the performance of the surface scheme is essential. The GMB data will be most useful for the ongoing process of improving the surface schemes of the driving climate models. It is therefore obvious that including CCI ECV parameters in such models should include both the models themselves, as well as the predictive capabilities.

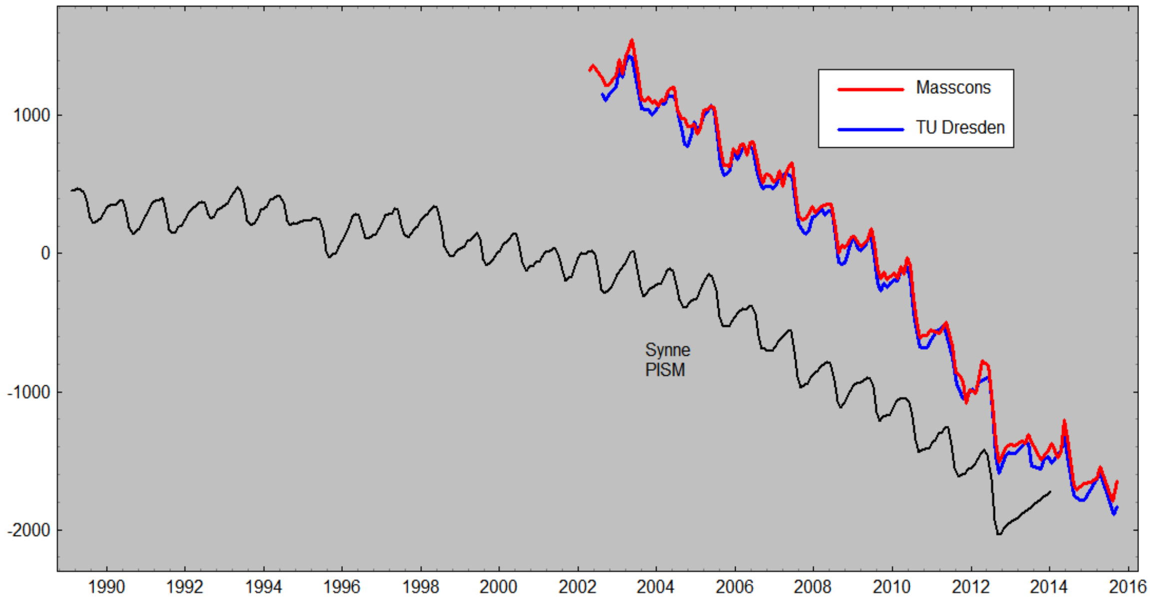

Fig. 2.1. Example of prediction of overall Greenland mass loss from the PISM glaciological-meteorological model (black), compared to two independent GMB time series (from DTU Space and Univ. of Dresden, respectively; the two different GMB methods treat leakage errors very differently); y-axis unit GT/year.

The consistent seasonal cycle showed in both GMB and SMB from a regional climate model (see Figure 2-2 below) suggests that at a whole ice sheet scale, the models are capable of capturing mass changes driven by surface processes. However the analysis also suggests that ice sheet models still cannot accurately capture ice dynamic processes on short temporal and spatial scales as shown by the mismatch in Figure 2-

1. Detailed exploration of the GMB data on a basin scale has also thrown up more surprises as explored in section 3.5.

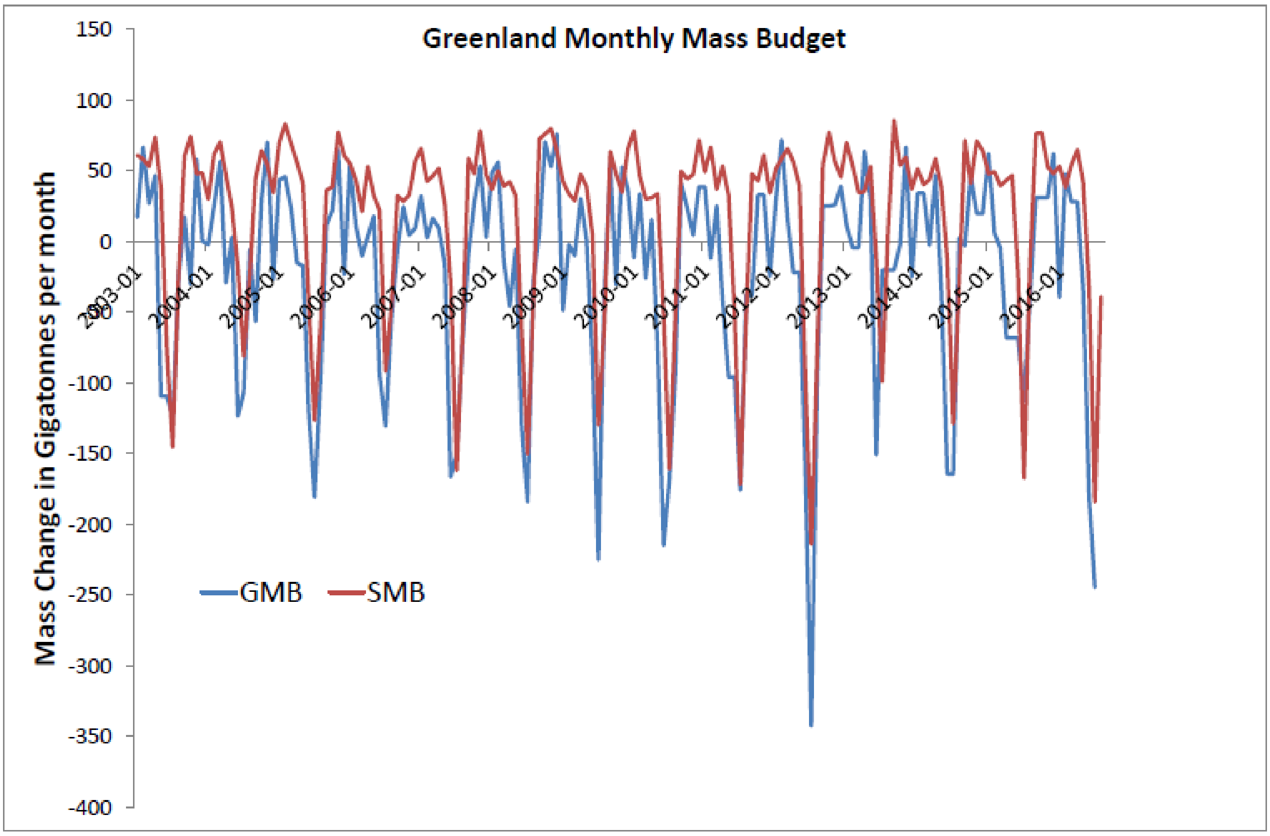

Fig. 2.2. Monthly surface (from HIRHAM5 regional climate model as shown in Langen et al., 2017) and gravimetric mass balance (from Univ. of Dresden) showing the importance of surface mass processes to the overall balance of the Greenland ice sheet.

In addition, the GRACE data is of clear value to the science community when it comes to communicating the effects of climate change on the Greenland ice sheet. The high precipitation in Greenland in the winter 2016-2017 (especially in October 2017) has been (mis)-used to claim that the high mass losses seen in Greenland have been reversed (see for example: https://climatefeedback.org/evaluation/another-arctic-ice-panic-world-temperatures-plummet-the-telegraph-christopher-booker/). However, the GMB data is unambiguous and presented on the polar portal along with the calculated daily surface mass balance is assisting in combating this misconception.

The GRACE data is particularly valuable as it shows the cumulative effects of mass loss over a longer period. The comparison between GMB and SMB in figure 2.2 shows that SMB is very much driving the total monthly budget with SMB generally higher than GMB in the winter months and the GMB, which includes dynamic processes generally lower in the summer months.

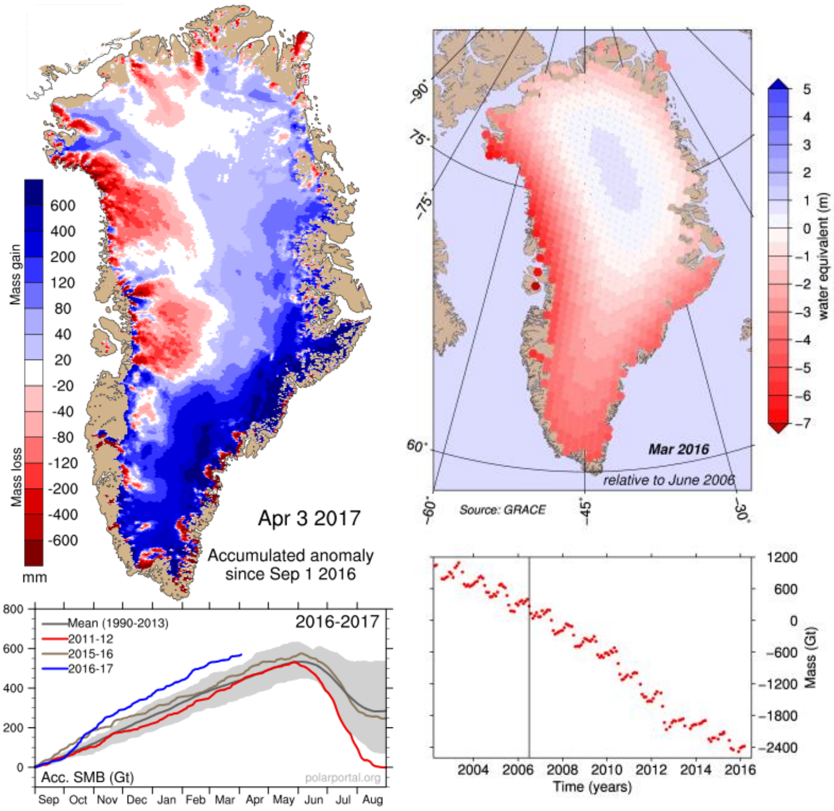

Figure 2.3 Figures showing the seasonally accumulated surface mass balance such as this one (left) have been shared widely on social media after the unusually heavy snow in Greenland over the winter 2016-17 period. This has led to some fundamental misunderstanding of the difference between surface mass balance and total mass balance. However, the visualisation of GMB (right) (both viewable on Polarportal.org) has helped to communicate the differences between surface mass balance and total mass balance.

2.2 Incorporation of data products

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 as the first year of phase 2 and into this year with a new update released in March 2017. The download statistics of the data archive up toQ3 2018 are shown in Figure 2.4.

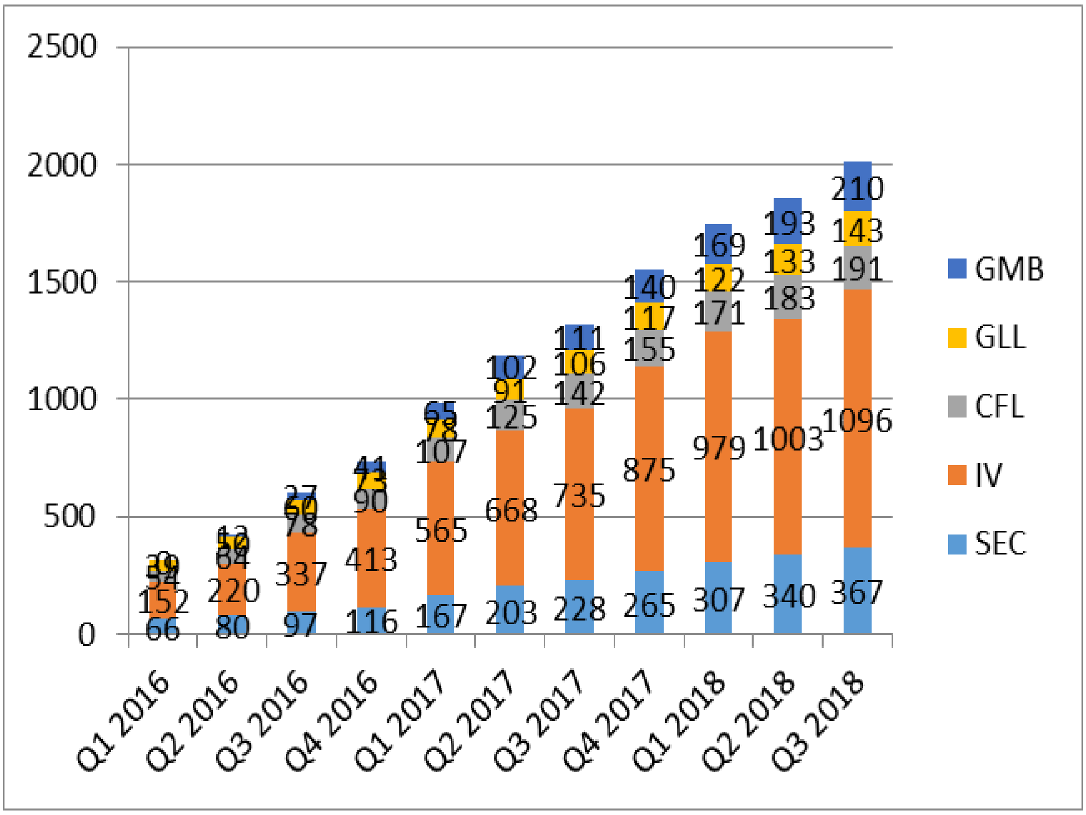

Fig. 2.4. Cumulative downloads of data products and total numbers per Q3 2018 from the project website (http://products.esa-icesheets-cci.org/).

3 Data integration into climate models

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).

3.1 Available data sets

In phase 1 of the project, a user survey gave information on needs and requirements concerning coverage as well as temporal and spatial resolution from the scientific community, see Table 3.1.1. The best possible match between the requirements stated by the user community and the availability of data resulted in data sets of SEC, IV, GLL and CFL data with the coverage and resolution stated in Table 3.1.2. These data sets have been validated in the phase 1 PVIR.

Within phase 2, these data sets will be expanded to encompass the coverage and resolution listed in Table 3.1. In addition to the phase 1 ECVs, gravitational mass balance (GMB) has been added to the suite of ECVs in phase 2.

	SEC	**IV**	**GLL**	**CFL**
MINIMUM spatial resolution	1-5 km	100 m-1 km	100 m-1 km	100 m-500 m
OPTIMUM spatial resolution	<500 m	50 m	50 m	50 m
MINIMUM temporal resolution	annual	Annual	annual	Annual
OPTIMUM temporal resolution	monthly	Monthly	monthly	Monthly
MINIMUM accuracy	0.1-0.5 m/yr	30	-	-
OPTIMUM accuracy	<0.1 m/yr	10	-	-
What times are observations needed	all year	all year	all year	all year

Table 3.1.1 User requirements for ECV parameters in phase 1 (from phase 1 URD)

	SEC	**IV**	**GLL**	**CFL**
Grid / shapefile resolution	5 km	500 m	200 m	200 m
Coverage region	Entire ice sheet	Coastal margin Northern basin Time series on two ice streams	5 northern floating glaciers	29 major outlet glaciers
Time coverage	Annual 5-year running means, 1992-	1995/2008 (margin) 1991/92 (basin) Near-yearly (ice streams)	Few epochs (1995/2008)	Annual
Main EO source	ERS-1, -2, Envisat (CryoSat pending)	ERS-1, ERS-2, Envisat ALOS/PALSAR	ERS tandem mission Envisat	ERS/Envisat SAR imagery
On web	Yes (filtering to be enhanced)	Yes	Yes	Yes

Table 3.1.2 Resolution and coverage of ECVs from project phase 1.

Parameter - Product	EO Input Data	Temporal Range	Temporal Frequency	Spatial Coverage	Spatial Resolution
SEC	ERS-1/2, ENVISAT, CS-2 and S-3 RA data	1991 – present day	monthly	Full GrIS	5km grid
IV – GrIS product	ERS-1/2, ENVISAT & RS-1/2, S-1 SAR data	1991 – present day	Every 2 years	Full GrIS	500m grid
IV – Ice stream product	ERS-1/2, ENVISAT & RS-1/2, TSX/TDX, S-1 SAR data	1991 – present day	seasonal	9 key ice streams[5]	500m grid
GMB – Gridded product	GRACE data	2002 – present day	monthly	Full GrIS	100km grid
GMB – Basin product	GRACE data	2002 – present day	monthly	Full GrIS	1 MB value per drainage basin
CFL	RADARSAT, S-1, S-2	2013 onwards	4 times per year	20+ key glaciers	250m shapefile
GLL	ERS-1/2, ENVISAT, TSX & TDX SAR data, CS2 altimetry data.	1992 – present day	decadal	all key ice streams that have/had grounding lines (see footnote)	250m shapefile

Table 3.1.3 Phase 2 user requirements from SoW.

		Spatial resolution				
Model type	**Model resolution**	**SEC**	**IV**	**CFL**	**GLL**	**GMB**
Global climate model	125km	5km	500m	250m	250m	100km
Regional climate model	40-25km	5km	500m	250m	250m	100km
High-resolution RCM	5km	5km	500m	250m	250m	100km
Very high-resolution non-hydrostatic RCM	1-3 km	5km	500m	250m	250m	250m
Ice sheet model in GCM/RCM	5 km	5km	500m	250m	250m	100km
Stand-alone ice sheet model	1-20km	5km	500m	250m	250m	100km
Finite element ice sheet model	> 1km	5km	500m	250m	250m	100km

Table 3.1.4 Resolution of ECV products compared to typical model resolutions.

Surface elevation change (SEC) data has so far been produced covering the entire ice sheet at a grid resolution of 5km. Data are available as annual values from 1991-2014 as well as an annual time series based on 5-year running means and over the course of phase 2 the temporal resolution will be increased to monthly values rather than annual. 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) (see figure 3.1, from Mottram et al., in prep).

The available spatial resolution is on a 5km grid. This resolution allows for main features of the ice sheet to be visible, however, many outlets are on a spatial scale of only a few kilometres and will 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 matter of model resolution impacts the dynamics of the models in the sense that even if proper model dynamics are available, the lack of resolution hampers the full impact of dynamics on the ice sheet geometry due to the poor resolution of outlets. Two mechanisms are available for ice removal; ice melt and ice flow through outlets. If the dimensions of the outlets are smaller than the available model resolution, the models will underestimate ice loss by the former mechanism and rely too heavily on ice removal by the latter. In the case of coupled climate models, the model resolution of the atmospheric part of the model is often around 80 - 100km in the polar regions for global models and 5-25km for regional models and with resolutions of the embedded ice sheet modules of 20-5km. These resolutions are coarser than or comparable to the available SEC data. However, climate and ice sheet models are steadily progressing towards higher model resolutions, with some runs (primarily for single drainage basins in stand-alone ice sheet models) performing even at sub-kilometre scale, where cci SEC data at higher spatial resolutions than the current choice would be desirable.

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 recently launched 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. This will be run at a resolution of 2.5km over a 24 year period from 1998. The SEC resolution is nonetheless still at a useful resolution for the CARRA project and it is expected to be included in the model evaluation.

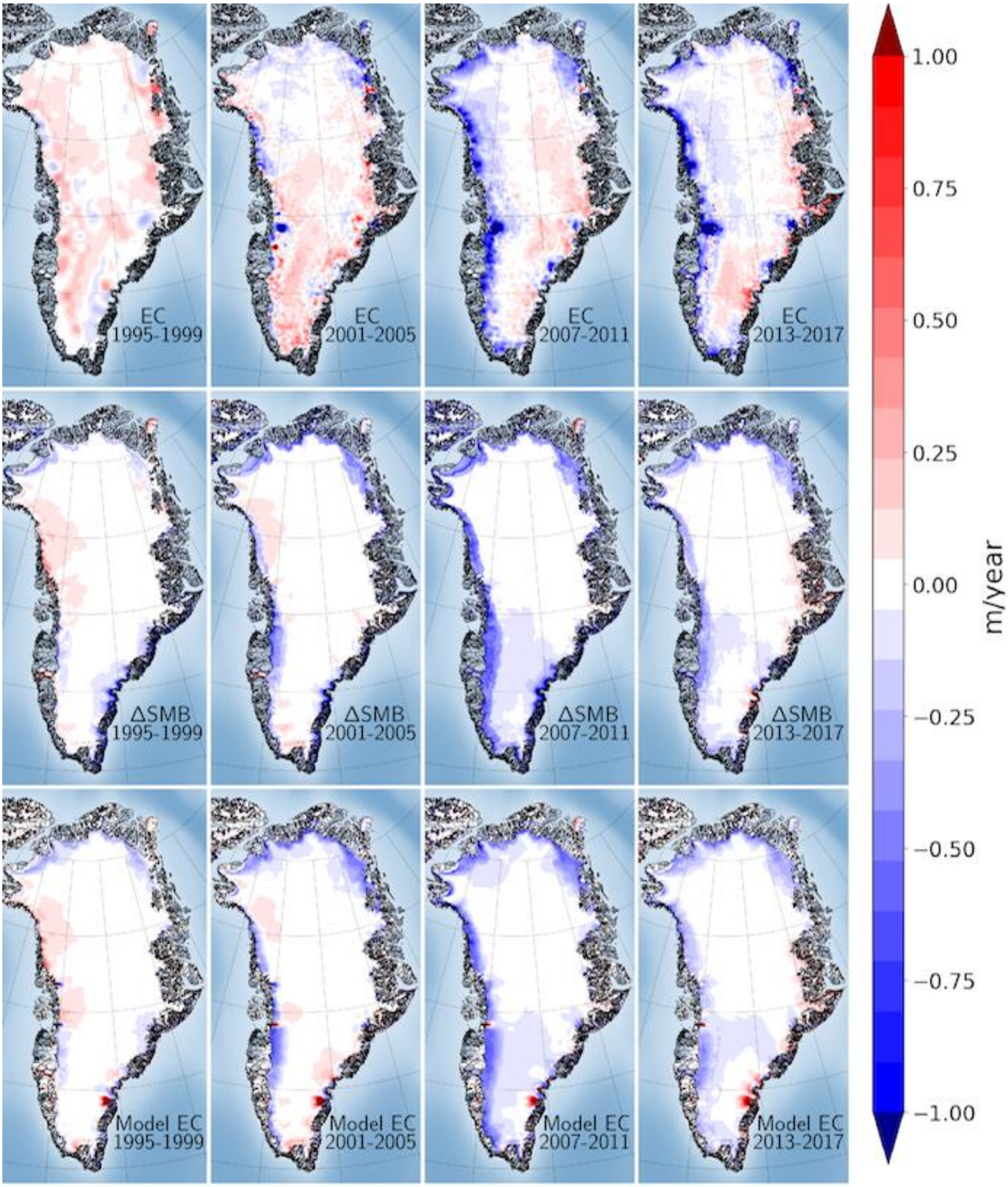

Figure 3.1 (Upper panel) Surface elevation of the GrIS from radar altimetry. (Middle panel) Change in surface mass balance in respect to the reference period (1982-1992) from HIRHAM5. (Lower panel) Change in volume as modeled by PISM when forcing PISM with HIRHAM5 surface mass balance and temperature.

In the case of the temporal resolution, data is currently available as annual values with the aim of achieving monthly resolution during the course of phase 2. Given that many ice sheet models, both stand-alone models and models imbedded in coupled climate models, are driven by annual means of surface mass balance and temperature, with some models running on monthly mean values, the temporal resolution is comparable to that of the models and is as such suitable for either model validation or use as constraints.

3.3 Ice velocity IV

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, Kangerdlugssuaq, Petermann, Nioghalvfjerdsfjorden, Storstrømmen, Upernavik and Zachariaes 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 will be an indispensable tool in research efforts to understand the dynamics of fast flowing ice streams (Aschwanden et al., 2016). Maps of ice-sheet wide coverage are extremely useful when dealing with questions of challenges provided by insufficient model resolution versus choice of model dynamics. The high resolution IV for outlet glaciers in combination with the grounding line and calving front data sets as well as atmospheric modelling has led to new insights, such as work by Rathmann et al (2017, see figure 3.2 below) on the glaciers of the north east Greenland ice stream (NEGIS) and Solgaard et al (in preparation) on Hagen glacier.

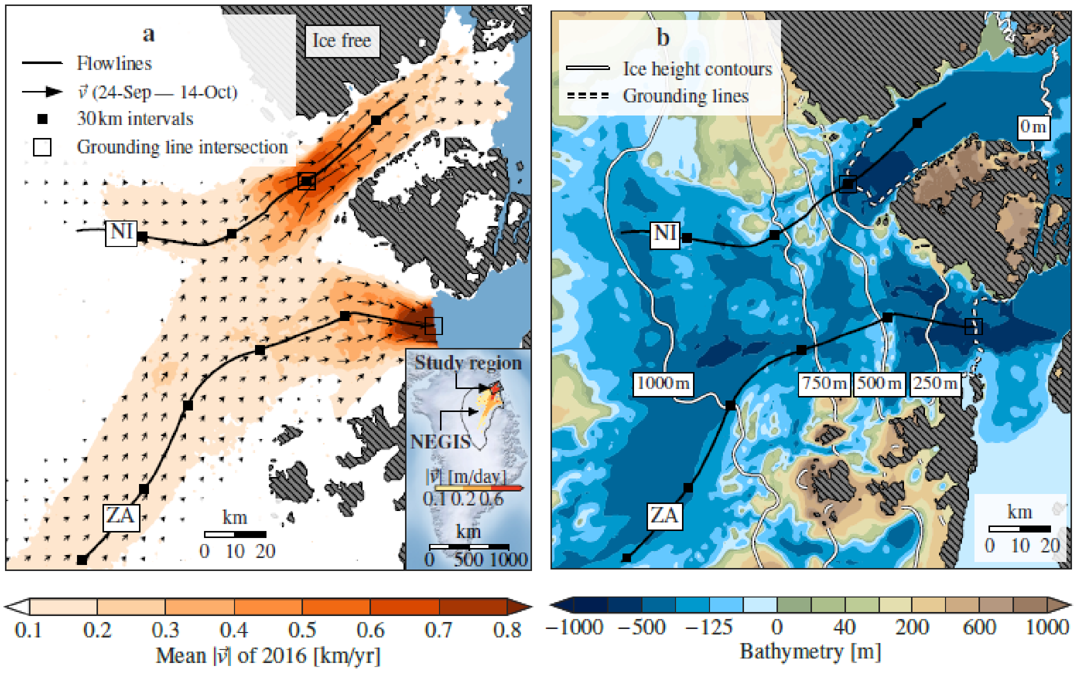

Figure 3.2 Ice surface velocities (left) for 2016 showing flowlines, and bed/surface topography (right) of Zachariæ gacier (ZA) and 79N (NI) icestreams with2016 grounding lines (dashed white lines) and calving fronts. From Rathmann et al. (submitted), this shows the value in combining multiple CCI data 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.

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 would be 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. 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. 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.

A similar study of Hagen glacier (Solgaard et al., in prep.) shows that while at some glaciers runoff is important for driving ice sheet dynamics, at other locations processes such as surge dynamics, likely modulated by basal hydrology, are more important controls on velocity. IV data over a long period at relatively high temporal and spatial resolution is thus very valuable as it allows the elucidation of different processes that are otherwise not possible to identify due to the time or spatial scale it operates on.

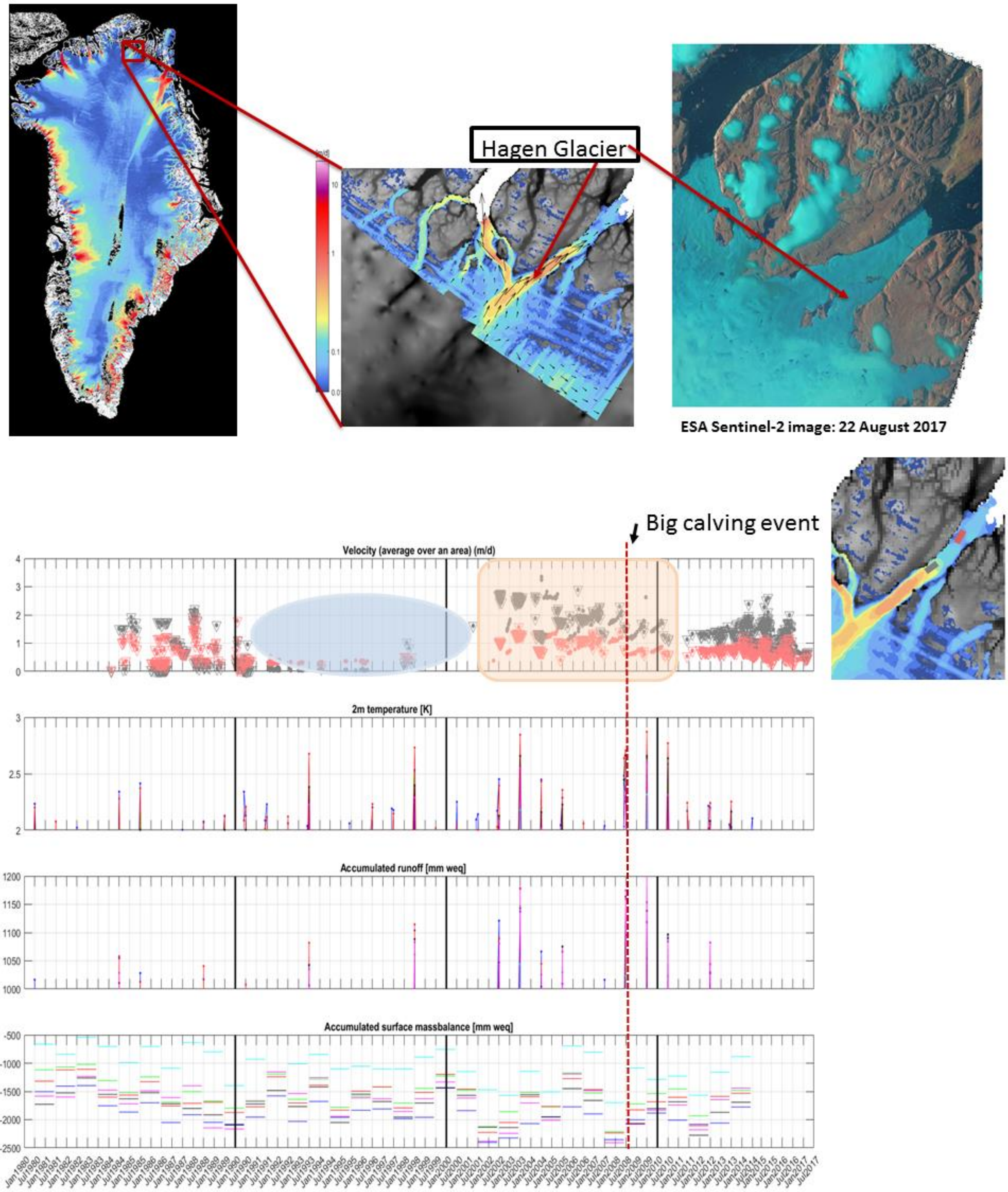

Figure 3.3 shows location and velocity of Hagen Glacier at the top and temperature, surface runoff and SMB (lower three panels) from the HIRHAM5 RCM. Velocity shows a cyclical pattern since the mid-1980s and while a large calving event in 2008 may be related to this, there is little evidence of a melt and runoff driven velocity acceleration.

3.4 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. Physically-based calving schemes applicable for Greenland have been developed based on crevasse-depth criteria (Benn et al., 2007) and implemented in 1D and 2D models (e.g. Nick et al. 2010), but so far, such schemes have not been included in large-scale 3d ice sheet models. This incorporation of physically based calving schemes for Greenland is an ongoing area of research, but until such schemes are routinely available, the mask approach continues to be used to determine calving from the Greenland ice sheet. High-resolution data sets of GLL and CFL are paramount to the production of realistic calving masks just as time series of these data sets are of crucial importance to the testing and validation of the physically-based calving schemes currently under development.

In ice sheet models, the location of the calving front is not an input parameter or model constraint; the location of the grounding line is determined from model dynamics and the bedrock topography. The CFL data is therefore not 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 3.2 as well as the work of Hogg et al. (2016) on Petermann glacier. The grounding line changes identified in Hogg 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.

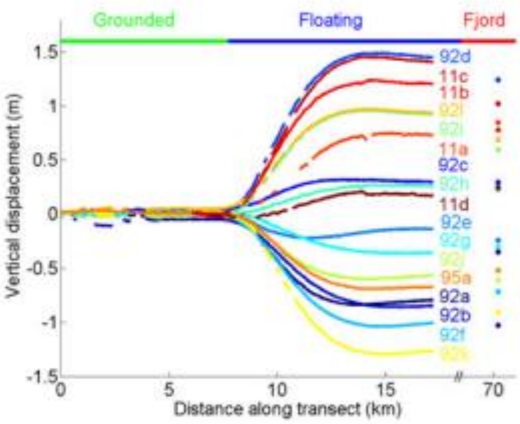

Figure 3.4 from Hogg et al., 2016 Relative vertical displacement along the transect E flow-line profile of the Petermann Glacier grounding zone, measured using 17 quadruple difference interferometry . Also shown (coloured dots) are relative tidal amplitudes at the same epoch as determined from the AODTM-5 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 (JPL et al., 2016), the CFL and GLL data products are very valuable contributions to scientists working on understanding the dynamics controlling calving outlet glaciers in Greenland (e.g. Muenchow et al., 2016).

The value of these products when combined is amply demonstrated by a project currently underway at DMI 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.

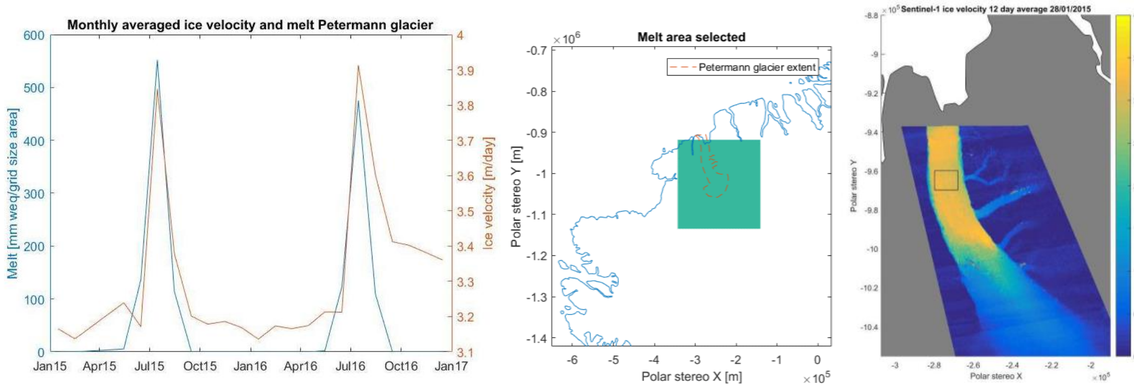

Figure 3.5 (Rosier et al., in preparation) Showing the strong relationship between velocity and melt rates at Petermann Glacier (left), in recent years, the area selected to calculate melt rates (centre) and the Sentinel 1 ice velocity map (right), the square indicates the location used to calculate average velocity.

3.5 Gravitational Mass Balance GMB

The GRACE-derived total mass balance is now available from the CCI products. However, based on the data release, e.g. through the Danish Polar Portal site (www.polarportal.dk) and several other US sites (e.g. GRACE Tellus site, http://grace.jpl.nasa.gov/), the GRACE data have 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 several 100km, it is useful to quantify *where* action is taking place, e.g. on the east, west or northern coastal regions (see figure 3.6 below), and climate change effects can also be followed very nicely when monthly solutions are animated into movies of accumulating mass loss. GMB, although it is only at the GCM resolution, does allow a time resolution which matches output from GCM/RCM and ice sheets models, as indicated in Table 3.1.4 above showing the typical resolutions needed for usefulness in different climate/ice sheet models. Evaluation of models using the GMB data will be a key part of the ISMIP6 modelling project.

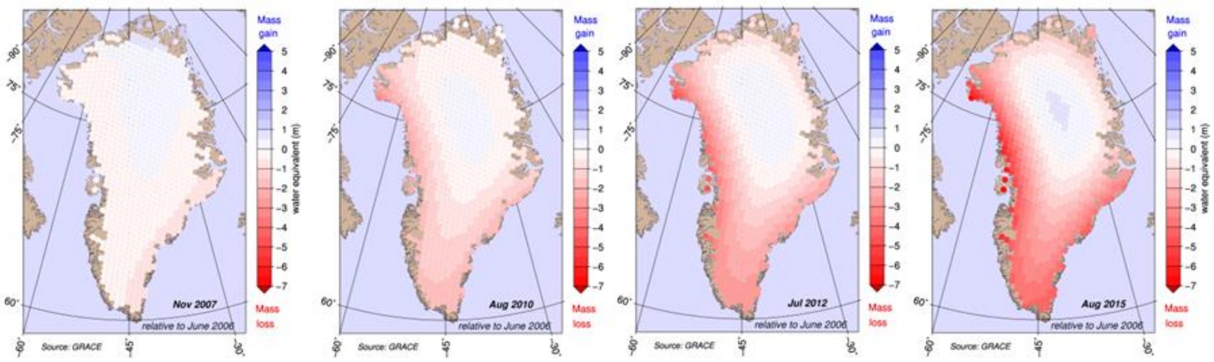

Fig. 3.6. Example of use of GRACE used to pin-point year-by-year mass loss regions in Greenland

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 3.7) 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. However, basin 8 shows a significant mismatch between HIRHAM and RACMO derived SMB, suggesting that the GMB may also be useful for evaluating regional climate models and for pointing out directions for future research (Mottram et al., in prep., a).

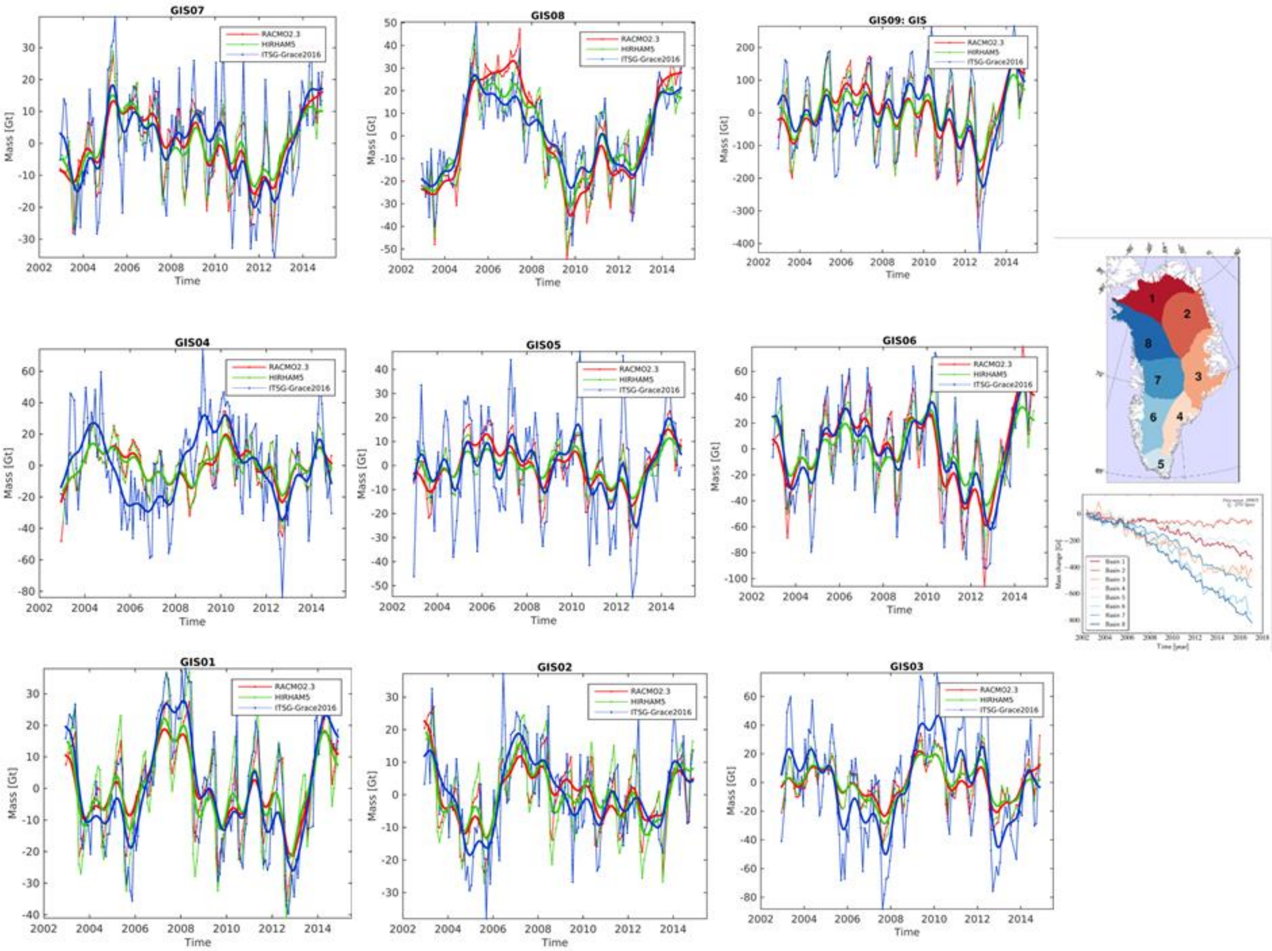

Figure 3.7 GRACE GMB and SMB from RACMO and HIRHAM5 shown on a basin scale (Groh, personal communication)- Large seasonal and interannual variations are shown in all three datasets. Curves have been smoothed with a quadratic function to assist interpretation.

4 Implementation of ECVs in models

As described in the preceding sections and summarized in Table the various ECV products have resolutions that are applicable in a whole range of different model types, ranging from global climate models to very detailed finite element ice sheet models. While there have already been numerous applications of the ESA CCI ECVs being used to elaborate on existing problems in Greenland ice sheet – climate research, there has as yet been relatively little research published where the ECVs are used directly in a model, either as initialisation, or as a boundary condition or for assimilation into a simulation. This may be due to the still relatively short time the ESA CCI data has been made available and given how long the publication cycle is. Therefore we present an overview of possible applications in various model types with examples where known. We also use this section to highlight possible synergies between ESA CCI and other international science projects that could benefit from the ECVs.

4.1 Climate model systems without actively coupled ice sheets

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 as part of the ice2ice project, a large ERC synergy project examining the links between Greenland ice sheet mass balance and ocean conditions.

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 4.1 where experiments in the HIRHAM5 regional climate model were carried out with modified topography (Mottram et al.,b in prep).

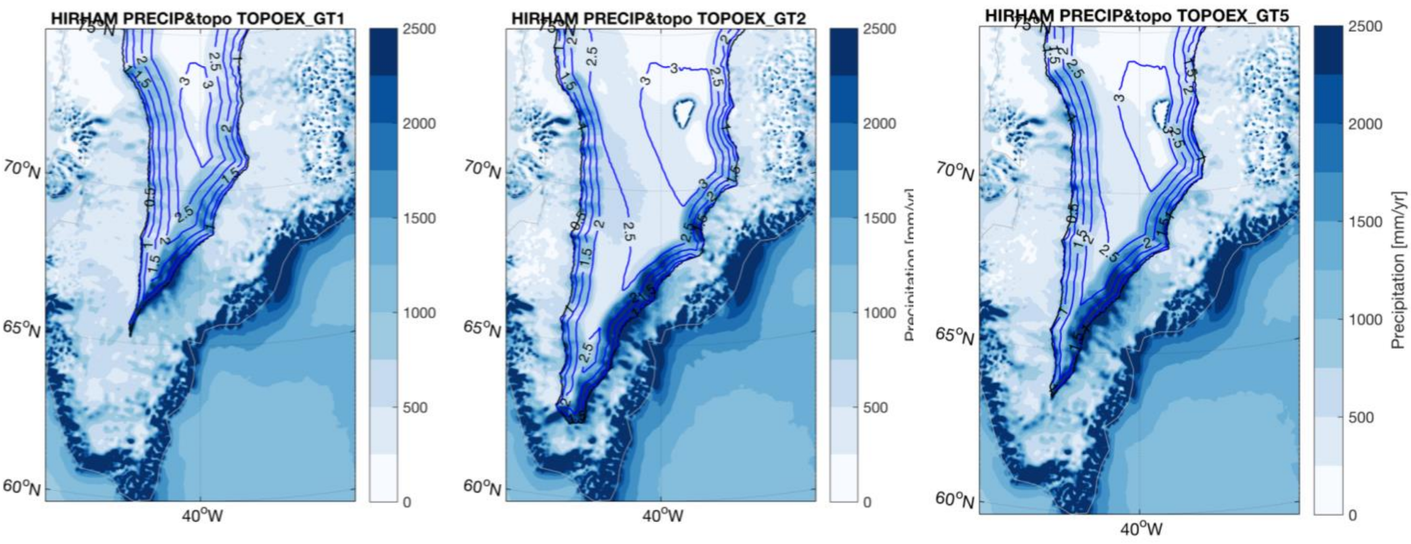

Figure 4.1 experiments with artificially reduced ice sheet topography (Mottram et al., in prep, b) confirm that for the most part, precipitation follows ice sheet margin positions.

In these experiments, the ice sheet elevation was maintained, but the extent of the ice sheet reduced. The model was then run for 5 years for each experiment. These experiments confirm the great importance of an accurate ice sheet topography for determining the amount of precipitation on the ice sheet with the consequent effects of surface mass balance.

4.2 Climate model systems with actively coupled ice sheets

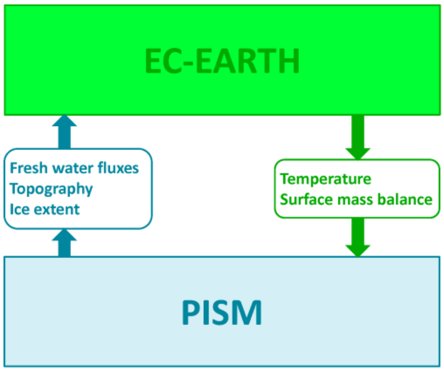

Figure 4.2 Flow diagram showing the parameters and fields used in an active coupling between an Earth system model (EC-Earth) and an ice sheet model (Svendsen et al. 2014, Svendsen et al. 2015).

In 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 course of a 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 to restrict spinup runs as well as validating the final post-spinup ice sheet states that serve as initial states for projection runs are in great demand)Price et al., 2017).

As is evident from the illustration of typical model grid resolutions shown in Figure 4.2 and Figure 4.2, resolution is an issue when considering global coupled ice sheet-climate models. In such coupled systems, the ice sheet model is by far the least computationally expensive part. Once the lengthy (uncoupled) spinup runs of the ice sheet are finished, the cost of running the ice sheet part of the coupled model system is comparatively low and resolution could easily be increased. However, the resolution of the climate model is an issue in this case given that the forcing fields for the ice sheet are made from climate model fields that need to be suitably downscaled. The resolution of the fields to be downscaled limits the resolution of the resulting fields. This makes it a challenge to resolve terrain with steep gradients in topography. Also, the energy balance calculations used to determine the forcing are not necessarily well-defined over open ocean, leaving coastal areas a challenge. This makes the production of suitable ice model forcings in steep mountainous or coastal terrains such as e.g. the Antarctic peninsula and the intricate fjord systems of the Greenland coast difficult to manage.

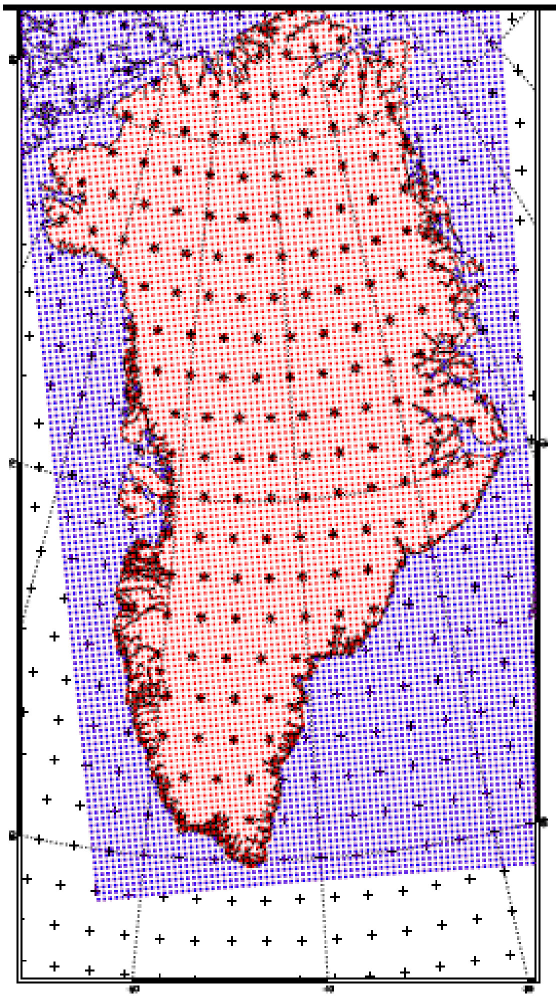

Figure 4.2 GCM model grid indicated by crosses (ocean points) and asterisks (land points) while grid points of the ice sheet model are indicated by the dots, blue dots representing ice-free ocean points, red dots representing ice-covered points.

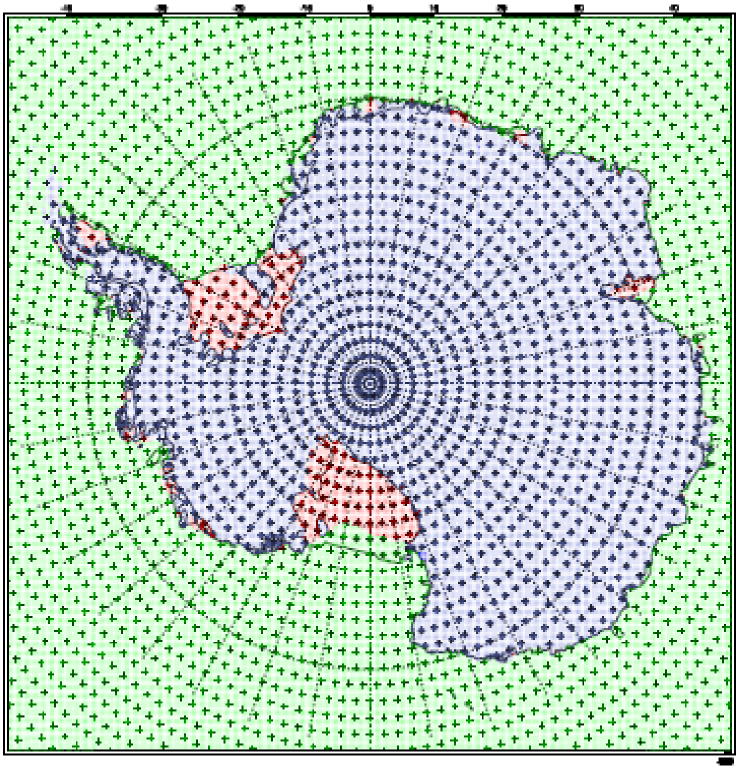

Figure 4.2 GCM resolution indicated by crosses and asterisks for ocean and land points, respectively. Coloured dots indicate the ice sheet model grid, green dots indicating ice-free ocean, red dots floating ice, blue dots grounded ice.

As can be seen from above, given the current resolution of the ice sheet states in global coupled ice-sheet-climate models, the current resolution of the produced ECVs is more than adequate for model validation and constraints on ice sheet initial states. There is, however, a great interest and need for time series that are as long as possible. In the case of the coupled EC-Earth-PISM system, an upgraded system with a T255L91 resolution for the atmospheric part and 5km resolution for the ice sheet is currently under development. Such a system would produce 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 will be 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 will provide valuable insights to the climate and ice sheet modelling communities and push the current standards for model capability, and the CCI data products will be an indispensable tool when undertaking the effort. High-resolution datasets of SEC, IV, GLL, CFL and GMB will serve as valuable constraints, initial states and benchmarks.

An example of different ways to evaluate ice sheet models run offline is shown below (figure 4.4) from a recently submitted paper by Aschwanden et al. (Submitted) where modelled ice velocities are given for a number of different ice sheet configurations, related to different representative concentration pathways as used in CMIP5. The observed ice sheet velocities and ice sheet area are given as a comparison to future possible ice sheet outcomes in the year 3000. As a 500 member ensemble was run in this study, the top row shows the percentile of different ensemble members that led to an ice sheet margin position. The lower row shows the modelled ice sheet velocity. Due to the uncertainties in both internal dynamics parameterisations, and in climate forcing fields, large ensembles of ice sheet model runs are required to better understand the system. The CCI data will likely play a crucial role in assisting in clarifying many of these processes.

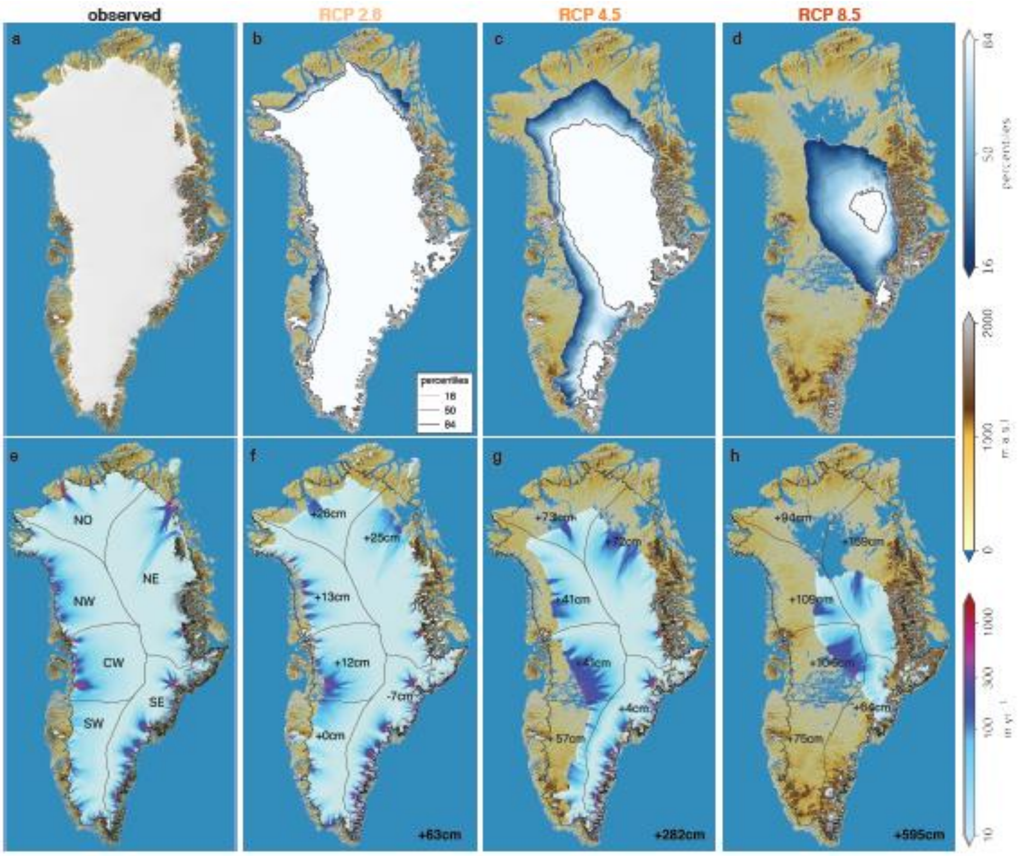

Figure 4.4 from Aschwanden et al. (submitted), showing modelled IV and observed IV as the ice sheet retreats.

4.3 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, see Figure 4.3. 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 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.

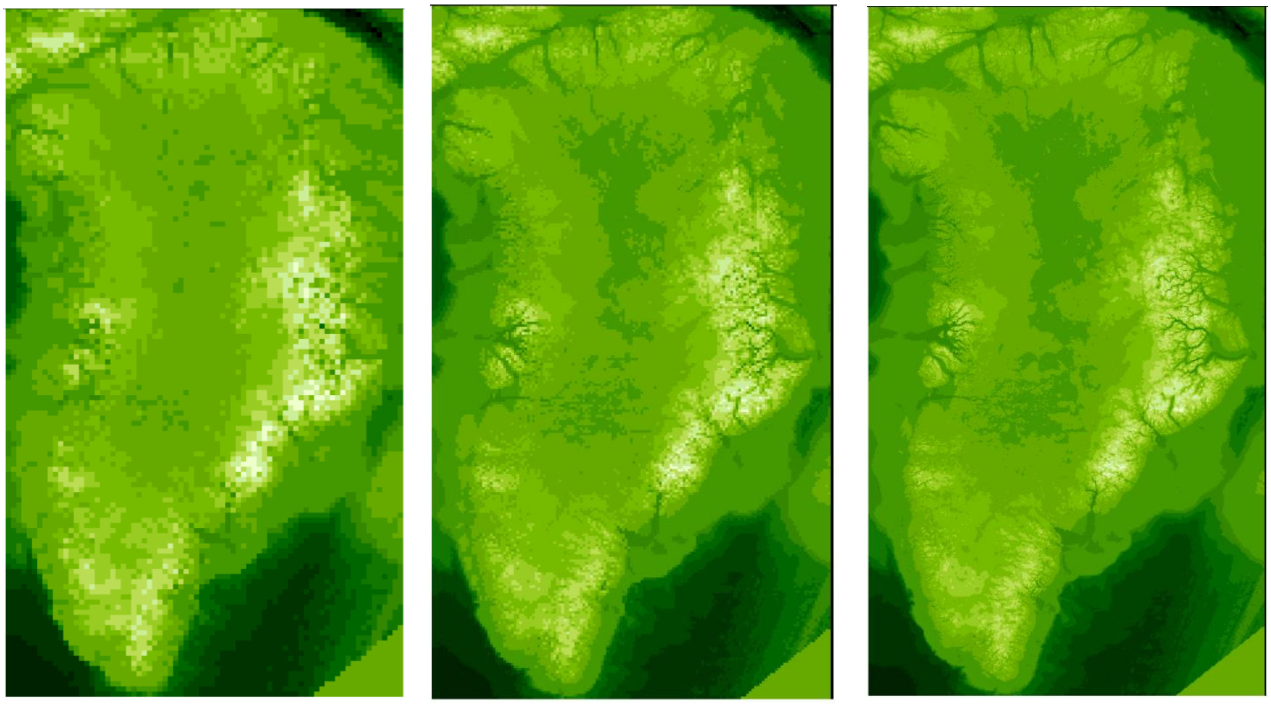

Figure 4.3 The bedrock topography from Bamber et al., 2013, at 20km (left), 10km (middle) and 5km (right) resolution.

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 has a significant impact on the flow fields, as can be seen

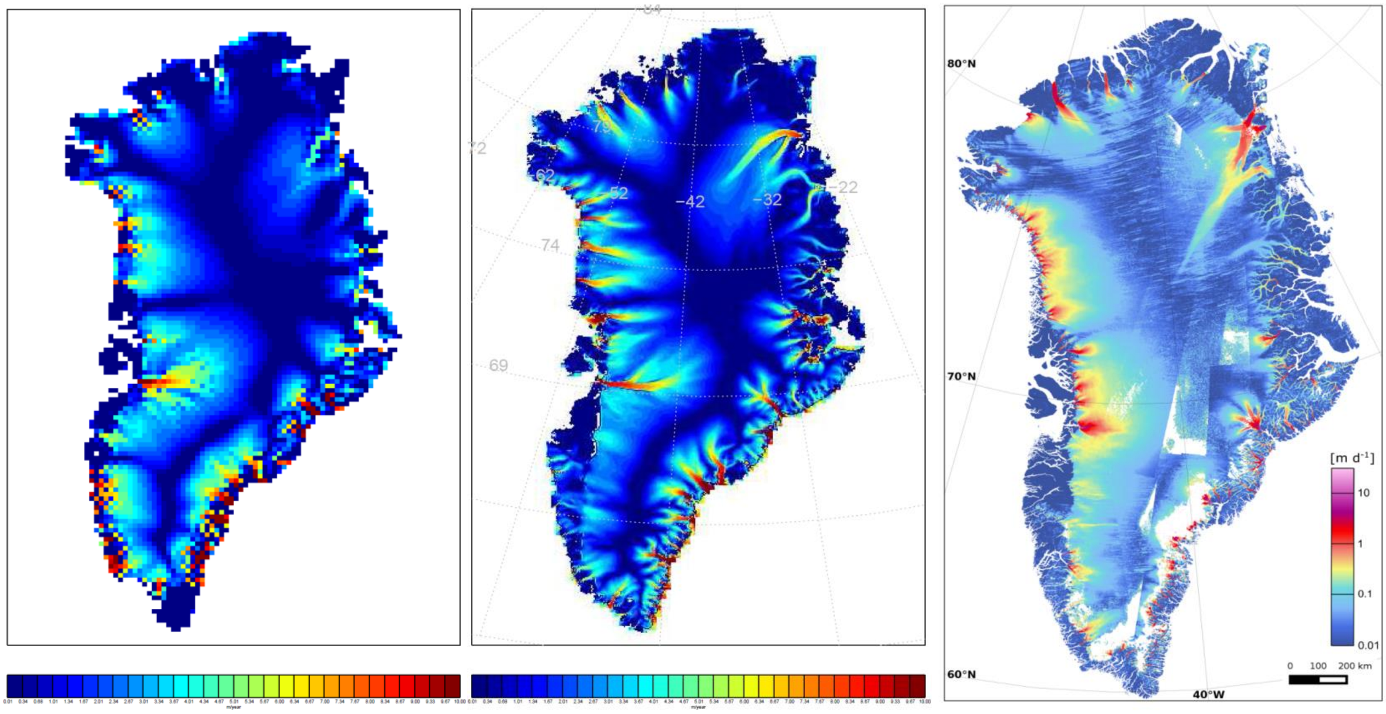

Figure 4.3 Left: Ice surface velocity in 2012 from the coupled model EC-Earth-PISM driven by the RCP8.5 scenario. The ice sheet model resolution is 20km. Middle: PISM stand-alone run at 5km resolution driven by HIRHAM5 run at 5km. Right: Observed velocities (IV).

in Figure 4.36, which shows the ice surface velocity from the PISM model at 20km and 5km grid resolution, respectively. Note that the 20km run and the 5km run are driven by different models, so the two ice sheet states are not directly comparable, but should merely illustrate the differences in the scale of motion. An example of a map of observed IV is shown as well for comparison. In the case of high-resolution runs, the IV, SEC and GMB products have substantial potential for validation studies, see also Fig.2-1, which showed preliminary comparisons between the cci GMB product and the corresponding total mass loss of the Greenland Ice Sheet according to the ice sheet model PISM run at 5km resolution.

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). An example of such an inversion is shown in Figure 4.7.

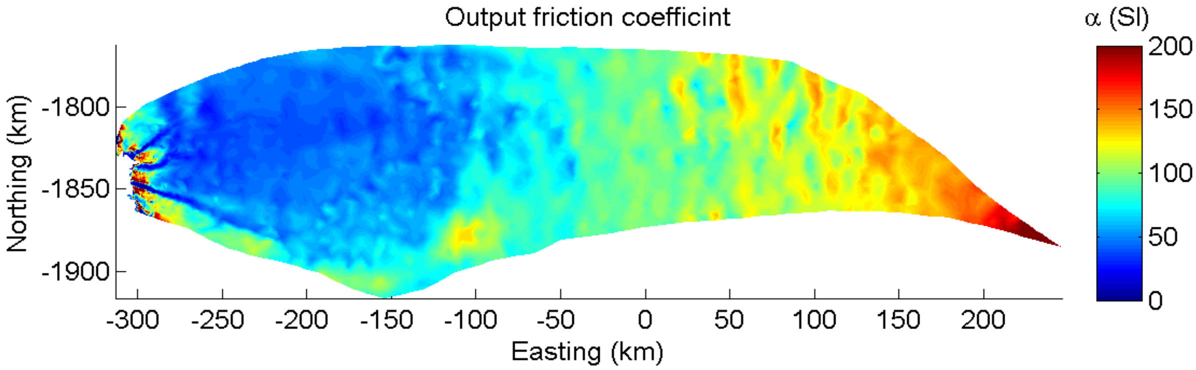

Figure 4.7 The basal friction coefficient in a Weertman type friction law, obtained from inversion of surface velocities using ISSM (Larour et al., 2012). In the extreme left, the fast-flowing (low basal friction) outlet glaciers of the Upernavik Isstrøm, Northwest Greenland can be discerned. From Larsen et al., 2014.

5 Recommendations

Phase 2 of the GIS_cci project has successfully improved and extended the existing data sets produced during phase 1 along with the introduction of an additional ECV, the GMB. Recommendations for resolutions have been given above. 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. As for the spatial resolution of the data sets, the need for an increase in resolutions 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 ice sheet models and single-basin modelling such as, e.g. inversion studies and various studies relating to melt water and exploitation potentials regarding hydropower.

The new GMB product with its estimates of the total surface mass balance changes will provide a most valuable tool in the development phase of coupled ice-sheet-climate models and the validation of these prior to projection runs.

5.1 Long-term additions to 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. In a coupled model setup, the ice sheet model is run solely by surface mass balance and temperature fields derived from the atmospheric part of the climate model (and, possibly, an oceanic forcing based on ocean temperatures). The atmosphere and ocean components receive information on the ice extent and topography along with fresh water fluxes from the ice sheet model. When modelling the atmosphere, everything hinges on radiative balances at the top of the atmosphere and at the surface. Consequently, the surface albedo is crucial to the model. 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.

5.2 Further uptake of ECVs in the scientific and wider community

Finally the use of the CCI data by the scientific community is increasing, along with the number of downloads. We have identified a number of opportunities for further research that the application of ECVs will certainly assist in. We also 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.

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. The polar open science conference was one such forum and there was significant interest in the data products also from the BBC natural history unit who are currently planning a new cryosphere based documentary series of Frozen Planet. They were particularly interested in the IV and CF data as they intend to focus on cryosphere changes at a range of scales. We will continue working with them as planning and filming move forward.

On a similar theme of public outreach, the GMB data has been combined with SMB data in a simple animated GIF in order to show the scale of the ice sheet mass loss over the GRACE period. The final presentation of this, it is hoped, will assist in communicating simply some of the main findings of the Greenland ice sheet CCI. If successful these could be expanded to, for example, the SEC data product.

6 References

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