ESA Climate Change Initiative (CCI)

Essential Climate Variable (ECV), Antarctic Ice Sheet (AIS)

Climate Assessment Report (CAR)

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Signatures page

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Change Log

Issue	Author	Affected Section	Reason / Description	Status
1.0	David Vaughan Lead Author, BAS Anna Hogg Co Author, UL	All	Document creation	Released to ESA on 2016-04-26
1.1	David Vaughan Lead Author, BAS Anna Hogg Co Author, UL	3.3.2, Figure 3.3.2-1 Updated	Review input from ESA	Released to ESA on 2016-04-30
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Acronyms and Abbreviations

Acronym	Explanation
AIS	Antarctic Ice Sheet
AIS_cci	Antarctic Ice Sheet CCI project
AP	Antarctic Peninsula
APMB	Antarctic Peninsula Mass Balance
AWI	Alfred Wegener Institute for Polar and Marine Research
BAS	British Antarctic Survey
CCI	Climate Change Initiative
CEOS	Committee on Earth Observation Satellites
CF	Climate and Forecasting
CFL	Calving Front Location
CMUG	Climate Modelling User Group
CRG	Climate Research Group
DARD	Dataset Access and Requirements Document
DInSAR	Differential Interferometry
DLR IMF	Deutsches Zentrum für Luft- und Raumfahrt (DLR) Remote Sensing Technology Institute (IMF)
DTU-GDK	DTU Geodynamics Group
DTU-MRS	DTU Microwaves and Remote Sensing Group
EAIS	East Antarctic Ice Sheet
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
EGU	European Geophysical Union
ENVEO	ENVironmental Earth Observation GmbH
EO	Earth Observation
ERS	European Remote Sensing Satellite
ESA	European Space Agency
GIS	Greenland Ice Sheet
GCOS	Global Climate Observing System
GLIT	Grounding Line Ice Thickness
GLL	Grounding Line Location
GOS	Global Observing System
GRACE	Gravity Recovery and Climate Experiment
GrIS	Greenland Ice Sheet
IAPG	Institut für Astronomische und Physikalische Geodäsie
ICR	Iceberg Calving Rate
ICSU	International Council for Science
IGOS	Integrated Global Observing Strategy

IMBIE	Ice sheet Mass Balance Intercomparison Exercise
IMF	Ice Mass Flux
InSAR	Interferometry
ICSU	International Council for Science
IOC	Intergovernmental Oceanographic Committee
IOM	Input-Output Method
IPCC	Intergovernmental Panel on Climate Change
IS	Ice Sheets
IV	Ice Velocity
MB	Mass Balance
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NetCDF	Network Common Data Form
NSIDC	National Snow and Ice Data Center
PSD	Product Specification Document
RA	Radar Altimetry
SAR	Synthetic Aperture Radar
SEC	Surface Elevation Change
SM	Surface Melt
SOW	Statement Of Work
SRD	Systems Requirements Document
STSE	Support to Science Element
S[&]T	Science and Technology AS
TUDr	Technische Universität Dresden
TUM	Technische Universität München
UCL	University College London
UL	University of Leeds
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
URD	User Requirement Document
URq	User Requirement
WAIS	West Antarctic Ice Sheet
WMO	World Meteorological Organization

1 Introduction

1.1 Purpose and Scope

This Climate Assessment Report (CAR) is delivered as part of Task 5 of the Antarctic_Ice_Sheet_cci (AIS_cci) project which is included in Phase 2 of the ESA CCI Program.

This document presents the results of the Climate Research Group (CRG) assessments of the AIS_cci data products at the end of the 3rd year out of a 3-year cycle project.

The scope is in accordance to document description in the Statement of Work (SoW) and the CRG Technical Note per 8th September 2015, both to be found in Appendix A of this document.

1.2 Applicable and Reference Documents

Table 1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	ESA/Contract No. 4000112227/15/I-NB, and its Appendix 1	Phase 2 of the ESA Climate Change Initiative, Antarctic_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 2: List of Reference Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
RD1	ST-UL-ESA-AISCCI-URD-001	User Requirement Document (URD)		
RD2	ST-UL-ESA-AISCCI-PSD-001	Product Specification Document (PSD)		
RD3	ST-UL-ESA-AISCCI-DARD-001	Data Access and Requirements Document (DARD)		
RD4	ST-UL-ESA-AISCCI-ATBD-001	Algorithm Theoretical Basis Document (ATBD)		
RD5	ST-UL-ESA-AISCCI-ATBD-002_RR	Algorithm Theoretical Basis Document (ATBD), Appendix Round Robin Experiments		
RD6	ST-UL-ESA-AISCCI-CECR-001	Comprehensive Error Characterisation Report (CECR)		
RD7	ST-UL-ESA-AISCCI-SSD-001	System Specification Document (SSD)		
RD8	ST-UL-ESA-AISCCI-SVR-001	System Verification Report (SVR)		

RD9	ST-UL-ESA-AISCCI-PUG-001	Product User Guide (PUG)		
RD10	ST-UL-ESA-AISCCI-PVIR-001	Product Validation and Inter-comparison Report (PVIR)		
RD11	ST-UL-ESA-AISCCI-CRDP-001	Climate Research Data Package (CRDP)		
RD12	ST-UL-ESA-AISCCI-CAR-001	Climate Assessment Report (CAR)		
RD13	ST-UL-ESA-AISCCI-PMP-001	Project Management Plan (PMP)		

Note: If not provided, the reference applies to the latest released Issue.

2 The CRG assessment approach

In the third year of the assessment, the products to be assessed were made available on data portals run by each ECV leader, and also on the CCI data portal. All were presented in the form that they are being distributed to the scientific community. They are thus entirely adequate to be assessed and a view as to their likely utility to the science community can be taken, even though to date they have not all been presented to the community in published papers. Work to publishing these valuable datasets ion peer reviewed journals is still on going, and the datasets have been presented to the community at a number of ESA and other science conferences.

For each product, an assessment of the sample data has been made, however not all members of the CRG were contacted to participate in the 3rd year assessment.

It is understood that the role of the CCI programme is to ensure the provision of datasets that have long-term value to the science community, and will not be rapidly superseded by similar products, and that the dataset should be sufficiently well-documented that they can, to the degree possible, be used alongside future data. To this end it is important that processing parameters and corrections used in the development of the products are thoroughly recorded and provided alongside the data. We found complete and annually updated documentation for the input data, algorithm and error approach used to generate each dataset. This is extremely valuable information, not provided alongside many other publicly available datasets, however as stated above it would be even more valuable for these methods to be written up in a peer reviewed publication that can be formally cited.

The following experts were involved in the CRG assessments of the Antarctic CCI products to date:

Anna Hogg, (UoL)

Stephan Cornford, (University of Swansea)

2.1 CCI products, regional assessment

A decade of high-profile research which has identified the glaciers draining into the Amundsen Sea (namely, Pine Island, Thwaites, Smith, and Kolher) has created and intense research focus in these areas. In particular, Pine Island Glacier has been the subject of five years of intense research from oversnow and shipborne researchers involved in the UK iSTAR programme (www.iSTAR.ac.uk) which is now completed. Similarly, over the next several years, a joint UK/US initiative will deliver an integrated field and modelling campaign on Thwaites Glacier. However, the value of the continental approach used in the CCI programme (Figure 1) is that it will allow diverse research teams to investigate new areas that are not those already under intense research focus, and to demonstrate the potential of CCI products to support these activities, the CRG undertook to consider the value of data generated by CCI in a region where rather few studies have been published, despite the fact that it is known to be an area of significant change.

The area selected for this study is the area comprises two areas of significant interest. The Getz Ice Shelf and the Sulzberger Coast. The first of these is an extensive ice shelf draining into the Amundsen Sea and, west of Cape Dart, into the unnamed coastal sea between Amundsen and Ross seas. This ice shelf is a 300 km long ice shelf that is structurally divided by a series of islands (and which might usefully be sub-divided for the purposes of naming as Larsen Ice Shelf A-D was in the mid-1990s). Getz ice shelf is thinning rapidly (Paolo et al., Science, 2015) but with a significant mountain range just inland, this ice shelf is not causing a widespread inland thinning in the way that the Amundsen Sea ice shelves to the east do. This ice shelf thus represents a quite different glaciological regime where a similar forcing is producing a quite different glaciological response.

The second neighbouring area, the Sulzberger Coast, also draining into the same unnamed coastal sea, is one where, even by the standards of the Antarctic continent, has been subject to very little research focus. Awkwardly remote from the nearest permanent stations and air facilities, this area is difficult to reach for any Antarctic operator. It is also largely without ice shelf thinning (Paolo et al, Science, 2015), but the sheer complexity of the morphology of the multiple islands embedded within Sulzberger Ice Shelf makes this a notable and potentially interesting area.

This CAR document is structured to first examine the spatial patterns of ice thinning and mass loss shown by the AIS_cci Surface Elevation Change (SEC) and Gravimetric Mass Balance (GMB) datasets in the study area. We then examine the Ice Velocity (IV and Grounding Line Location (GLL) AIS_cci datasets to investigate if by combining all 4 AIS_CCI essential climate variable in one dedicated study, we can learn something new about the physical processes driving environmental change in this remote and unstudied region of Antarctica. The Getz and Sulzberger study areas are both contained within the Zwally drainage basin number 20. Finally, we discuss the findings

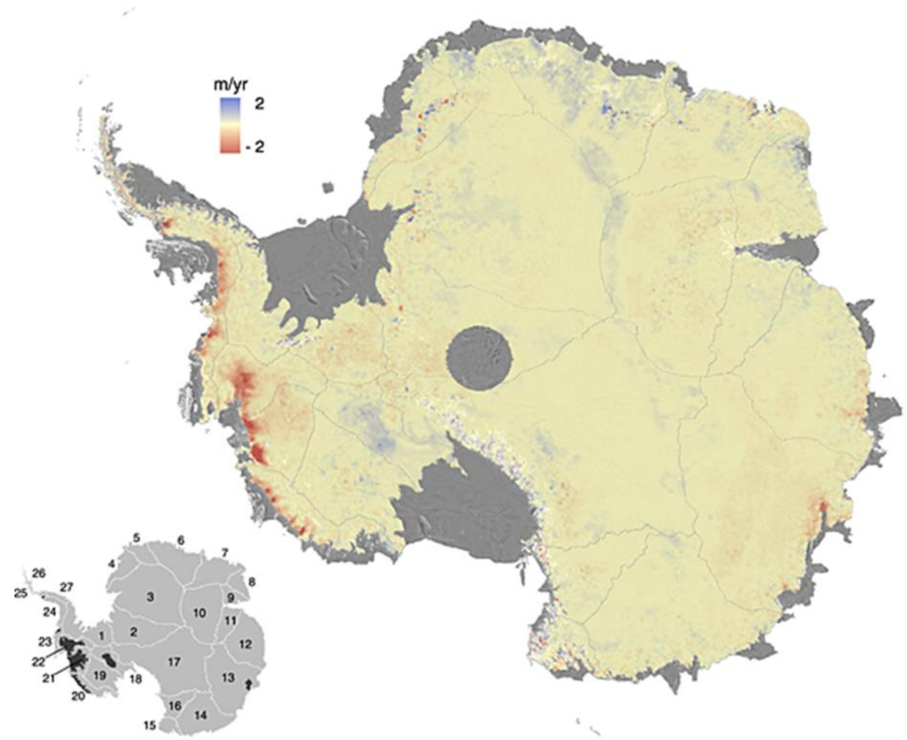


Figure 1. *Thinning rates for Western Amundsen Sea Sector 2010-2013 (McMillan, 2014).*

shown in the AIS_cci datasets with respect to other results in the recently published literature.

3 Surface Elevation Change (SEC) and Gravimetric Mass Balance (GMB)

3.1 The SEC and GMB data products assessed

Surface elevation change provided the first credible measurement of ice sheet imbalance in Antarctica (Wingham et al, 1998) and thus provides an important observable of change. It is arguable that it offers the longest potential time series for a continent-wide observation. However, the physical interpretation of this observation is not straightforward. At any point on the ice sheet the surface elevation change is a function of any dynamical imbalance (on a variety of timescales) variations in precipitation and variations in firnification of the surface layers of the snow.

Two data products have been subject to assessment, these are gridded products and basin-integrations. The SEC product spans the 25 year epoch for which radar altimetry measurements were acquired, however the GMB dataset spans a shorter 14 year epoch over which the GRACE satellites have been in operation, between 08.2002 and the present day.

3.1.1 SEC and GMB gridded product

These data are provided on 5-km by 5 km grid for the full 25-year period (Figure 2), and the gridded GMB data are provided on a coarser resolution 50km by 50 km grid, again for the full period of GRACE operation (Figure 3).

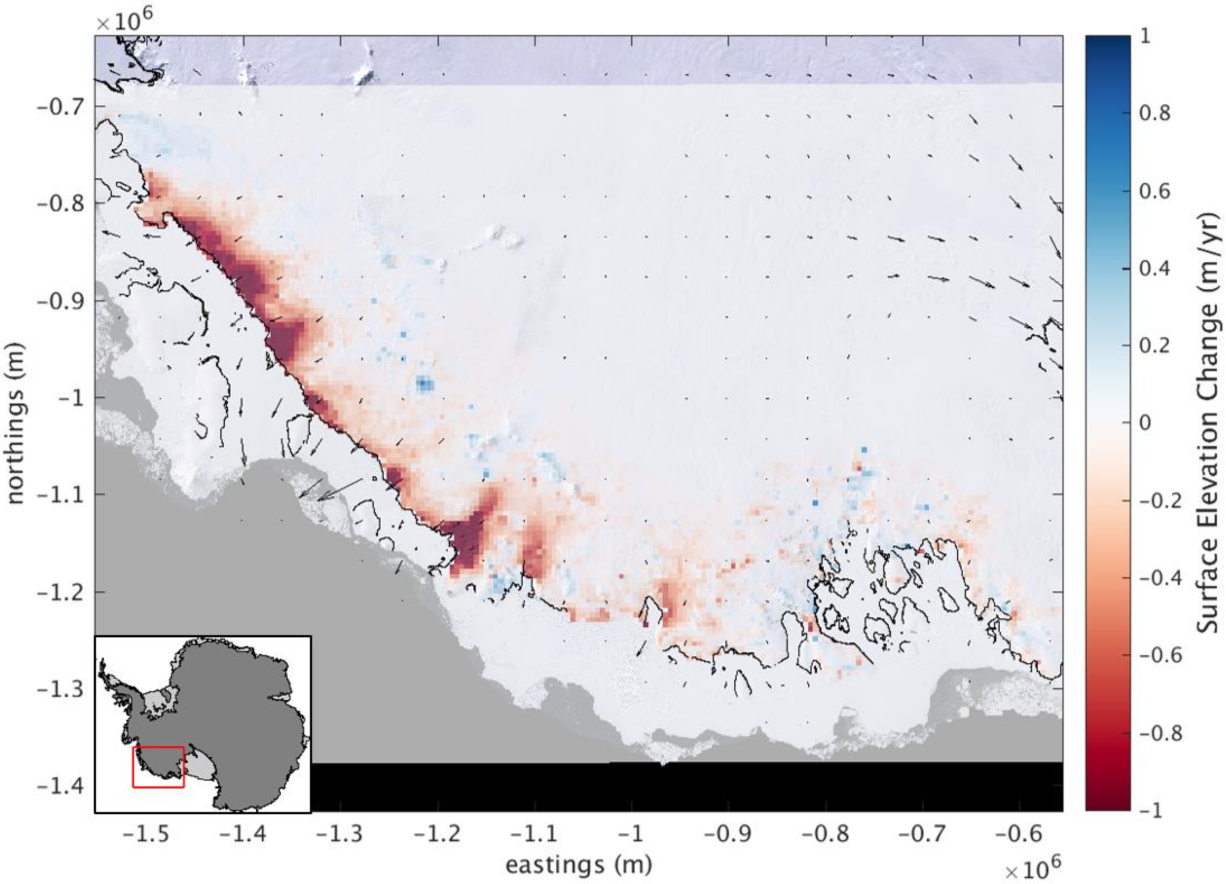


Figure 2. *Surface elevation change measured by radar altimeter satellites in the Getz and Sulzberger basin of west Antarctica (red blue colour scale). Ice velocity vectors (black arrows) and the grounding line location (black solid line) are also annotated. The Landsat mosaic of Antarctica (LIMA) is used as the background image, and study area location is also indicated (thumbnail insert).*

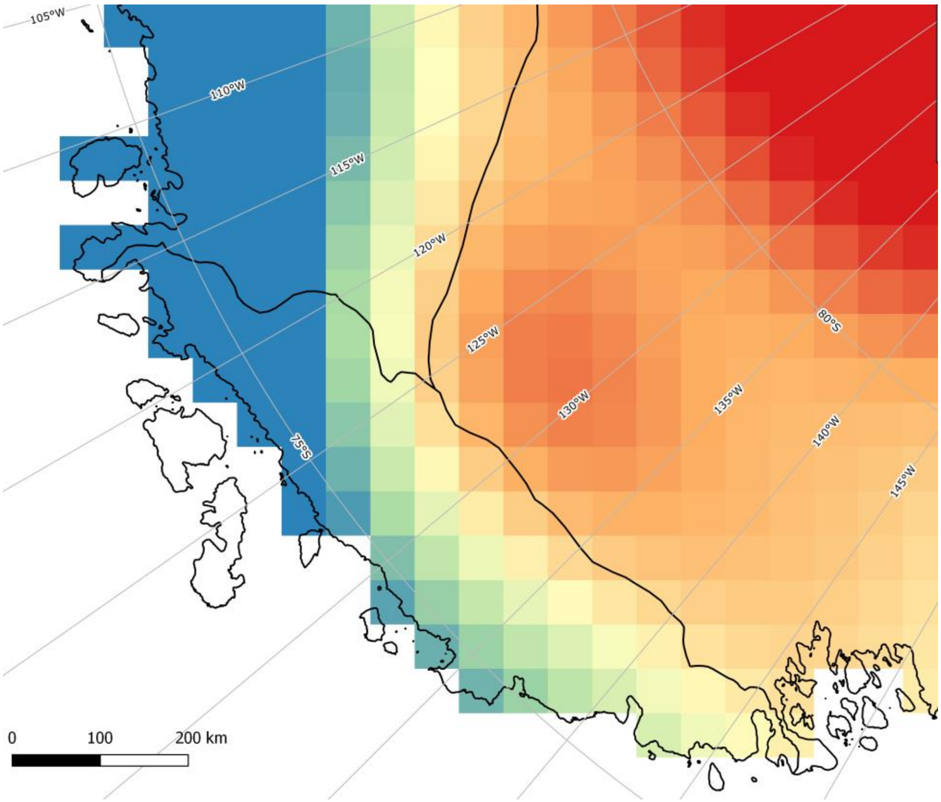


Figure 3. *Gravimetric mass balance measured by GRACE satellites in the Getz and Sulzberger basin of west Antarctica (red blue colour scale). The grounding line location (coastal black solid line) and drainage basin boundary (inland solid black line) are also annotated.*

The most obvious difference between both SEC and GMB datasets is the spatial resolution of both products. The finer 5km by 5km spatial resolution of the SEC product (Figure 2) clearly shows that in the Getz basin, the dominant surface elevation change signal is for thinning rather than an increase in the elevation of the ice surface. This is corroborated by the GMB data which shows a predominantly negative mass change signal for this region. In addition to the broad, large scale pattern, the fine spatial resolution of the SEC dataset reveals that ice thinning is concentrated in the more steeply sloping coastal region near the ice sheet grounding line. Thinning rates in this study area exceed 1 meter per year, which is a significant signal within the context of full continent wide elevation in Antarctica. Moreover, the pattern of thinning is clustered around 8 discrete, focussed 'hotspots', which are likely to coincide with individual flow units along the Getz coastline. This will be investigated in further detail when evaluating all four AIS_cci products together in the summary section of this document.

3.1.2 SEC and GMB basin time series product

We examined the basin wide time series for the Getz and Sulzberger study area only (basin 20), to evaluate elevation change and mass change on quasi-monthly time steps (Figure 4).

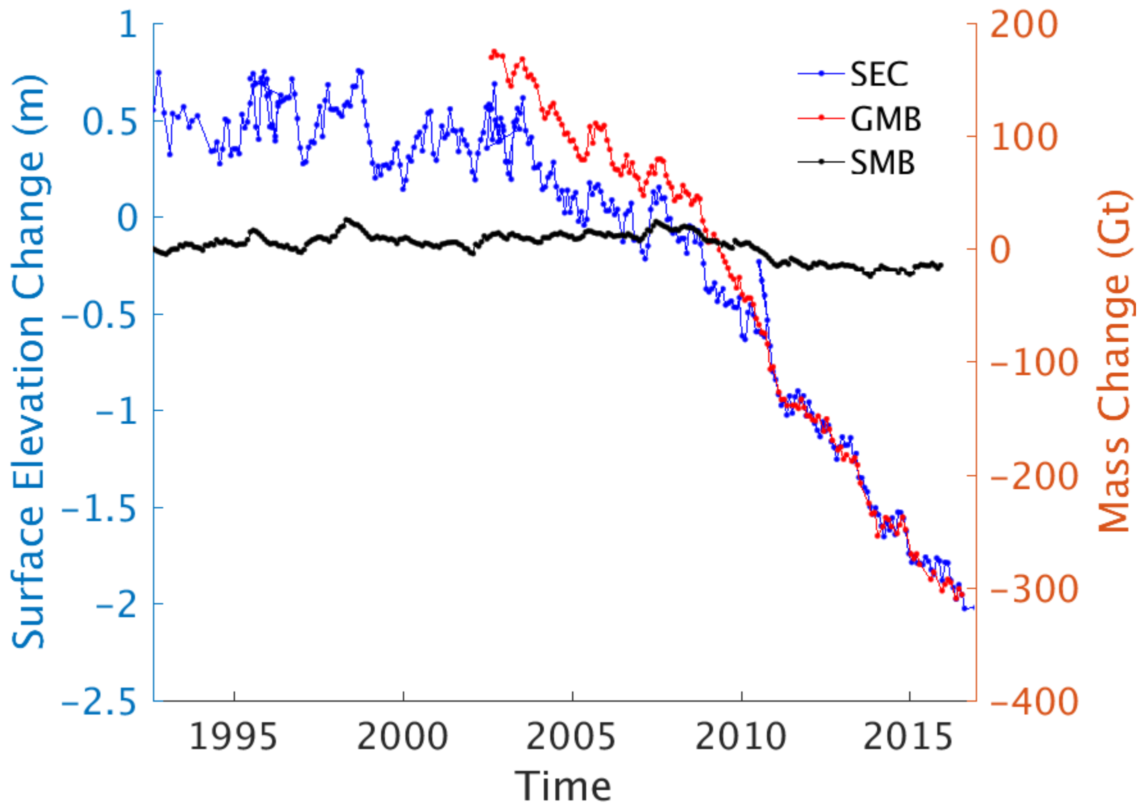


Figure 4. *Time series of surface elevation change (blue) measured over a 25-year period by radar altimetry satellites, gravimetric mass change (red) measured over a 14-year time period by GRACE satellites in the Getz and Sulzberger basin of west Antarctica. We also extracted the surface mass balance snowfall input to the basin as estimated by the RACMO model (black).*

Figure 4 shows once again that although the AIS_cci SEC and GMB data products are not provided in the same units (SEC is in meters, GMB is in gigatonnes), the temporal variability of both datasets shows the same trend of both decreasing ice surface elevation and increasing mass loss from this sector of Antarctica. The SEC time series shows that while there is relatively large variability, overall the elevation change remained relatively constant at 0.5 meters during the early 1990's (1992 to ~2002). However, after the mid 2000's there was a regime change in this basin and over 2 meters of ice thinning has occurred between 2002 and the present day at the basin average scale. The AIS_cci GMB data show that since 2002 over 400Gt of ice has been lost from the Getz & Sulzberger basin. This represents a large 30 % proportion of the total mass loss signal for the Antarctic Ice Sheet measured since 1992 (Shepherd et al, 2011).

We examined the snow input into the Getz & Sulzberger basin over the same time period by extracting surface mass balance anomaly from the RACMO climate model (Figure 4). This data shows that there has been no significant change in the snow mass input into the drainage basin. This is extremely interesting because a decrease in ice sheet surface elevation can be caused by two distinct processes, namely; less snow mass input to the basin, or more ice mass exported from the basin via fast flowing ice streams. Our result, (i.e. that the SMB input has not changed, but the elevation and mass change has become negative over the past 14 years), may indicate that the process responsible for this regime shift is linked to dynamic instability. We will examine this hypothesis in the IV and GLL section of this document.

3.2 Recommendations for SEC and GMB product improvement

We have no major recommendations for either dataset as both are highly suited to the glaciological applications that they are intended to be used for, and the product formats and metadata provided for both datasets are extremely clear and user friendly. The only major recommendation that we would have is that both datasets continue to be extended in time in the future as new EO data is acquired. For both datasets, there would be added value in a higher spatial resolution product, however we recognise the clear trade off that has been made when generating these Level 3 datasets to optimise product quality against the resolution of the input raw satellite dataset. Our recommendation is therefore to ESA, to a) ensure that both gravimetry and altimetry data continues to be acquired over the full Antarctic ice sheet, and b) that the altimetry and gravimetry instruments used acquire this raw EO data, operate in imaging modes with *the same or improved* spatial resolution than the CryuoSat-2 and GRACE satellites currently in operation.

4 Ice Velocity (IV) and Grounding Line Location (GLL)

4.1 The IV data products assessed

Ice velocity products for the Getz Ice Shelf and Sulzberger Coast for the 2017 AIS_cci CAR, comprises a series of 6 distinct ice velocity maps generated from ERS-1, ERS-2, Alos Palsar, and Sentinel-1 data, acquired in the 1990's, 2005/6, 2010/11 and 2016/17, as summarised in Figures 5 and 6.

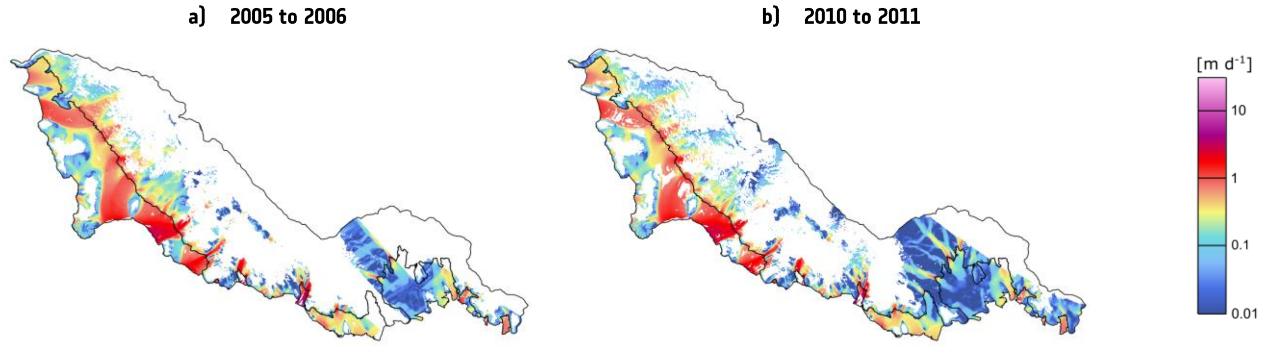


Figure 5. Ice velocity measurements generated from ALOS PALSAR data acquired over the Getz and Sulzberger basin in the mid and late 2000's.

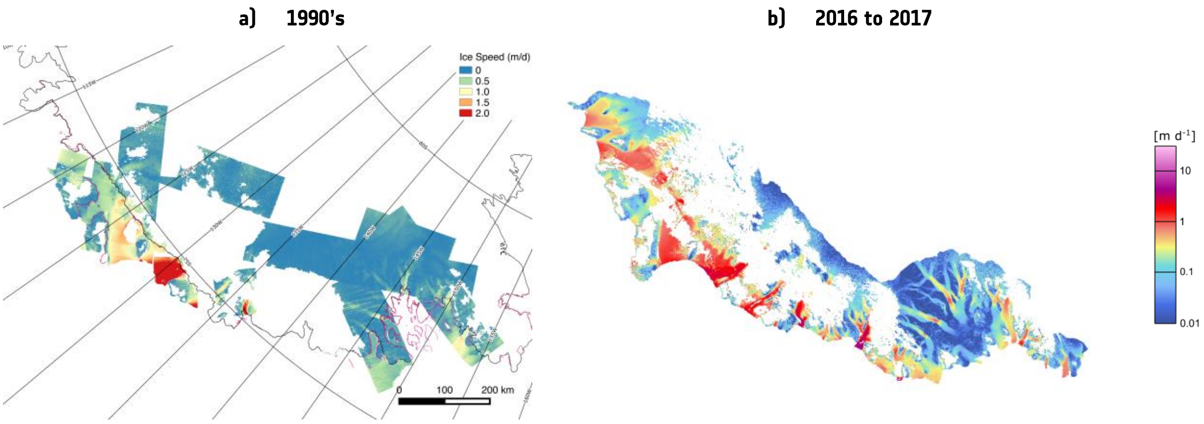


Figure 6. Ice velocity measurements generated from ERS-1/2 and Sernitnel-1 data acquired over the Getz and Sulzberger basin in the early 1990's and the present day, respectively.

A notable feature of the dataset is seen inland of the Getz Ice Shelf. Here, over all time periods, the spatial coverage of the product is somewhat patchy on the interior of the ice sheet. This is particularly noticeable in Figure 6a where the raw SAR data acquisitions do not cover the full basin therefore it is inevitable that measurements cannot be made in regions with no data. However, in all other time periods (Figures 5a, 5b and 6b), raw SAR data was acquired over the full basin area, however the feature tracking data processing technique is not able to retrieve a velocity measurement. Figure 7 illustrates this issue, by showing the spatial variability of the number of ice velocity measurements per grid cell that were used to create the mean velocity map for the Sentinel -1 epoch. The failure to retrieve ice velocity measurements in the interior of the Getz Ice Shelf is probably a result of the absence of surface features in this area, combined with meteorological events such as snowfall and blowing snow which can obscure features that do exist, thus reducing the effectiveness of the tracking algorithm.

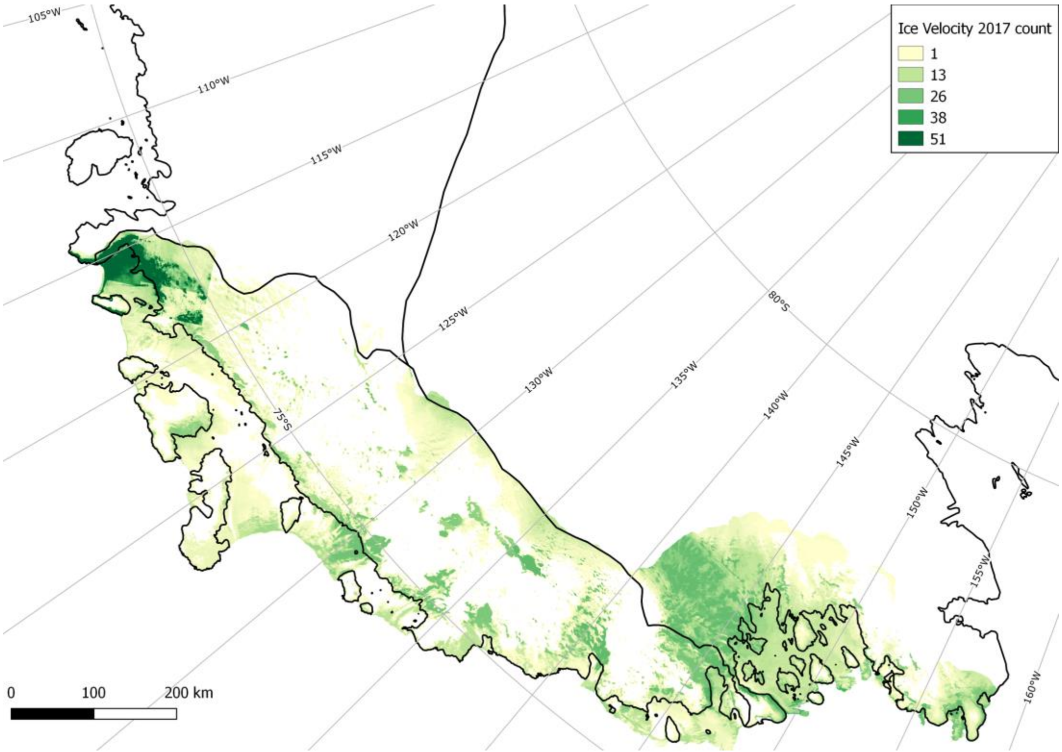


Figure 7. *Number of ice velocity measurements per grid cell for the Getz & Sulzberger drainage basin in West Antarctica during the2016-2017 Sentinel-1 period of operation.*

A similar pattern is not visible on the interior of the Sulzberger Ice Shelf, where a network of previously unknown (D. Vaughan, personal communication) of relatively slow flowing, but well defined enhanced flow units can discriminated up to ~100 km upstream of the grounding line. On investigation, these features were visible in the Measures dataset (Rignot et al, 2011), but now appear more clearly defined and with subtleties not previously visible.

One feature of particular interest, perhaps worthy of further investigation is shown in Figure 8. This is an apparent 'over-printing' of one flow unit by another. This could potentially be the relic of an earlier flow pattern whose presence is still visible despite being over written by a new system of flow. If proved, this would be a novel feature not previously observed in the Antarctic ice sheet, and with the potential to open new avenues of research, if similar features can be identified in the CCI VI product elsewhere. However, a note of caution, it is also possible that the suggestive pattern is simply a coincidental juxtaposition of flow units and further investigation will be required to establish this with certainty.

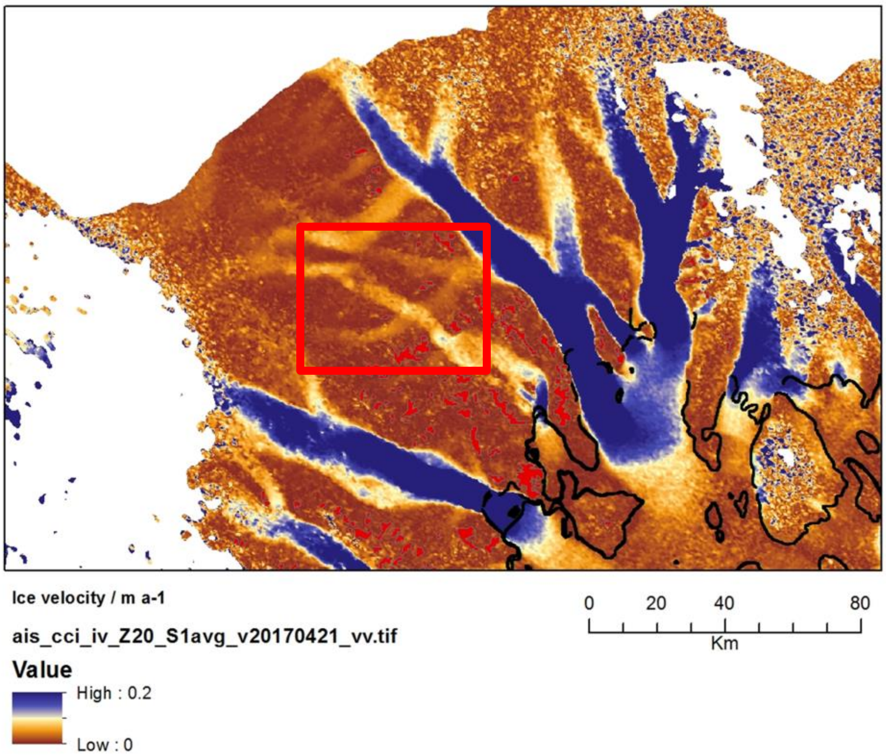


Figure 8. *CCI velocity on the interior of Sulzberger Ice Shelf. Note potential overprinting in ice flow velocity pattern in centre of the image, highlighted in red square. This feature is not previously identified and could represent the survival of a pre-existing flow pattern after the establishment of a new one.*

4.2 The GLL data products assessed

The grounding line is the transition between the grounded ice sheet and the floating ice shelf. Strictly speaking, the grounding is the horizontal locus of the points at which the ice goes afloat, marking the boundary between grounded ice sheet and floating ice shelf. Whilst glaciologists often refer to the grounding line, there is, however, a sometimes tasit understanding that this may not be precisely defined. Indeed, in many areas, the grounding line may migrate several kilometres within a tidal cycle, in other areas, glaciological configurations may mean that the ice is neither fully floating nor fully grounded, but partially supported. Either condition would lead to the grounding line more properly being referred to as a "grounding zone".

The AIS_CCI GLL dataset was provided as a shapefile with substantial and useful metadata. The AIS_cci GLL dataset in year 2 of the project is considerably enlarged around the whole Antarctic continent, however for the purposes of this climate assessment report we will evaluate only the datasets available in basin 20 as shown in figure 9 (below) for the Getz and Sulzberger sector.

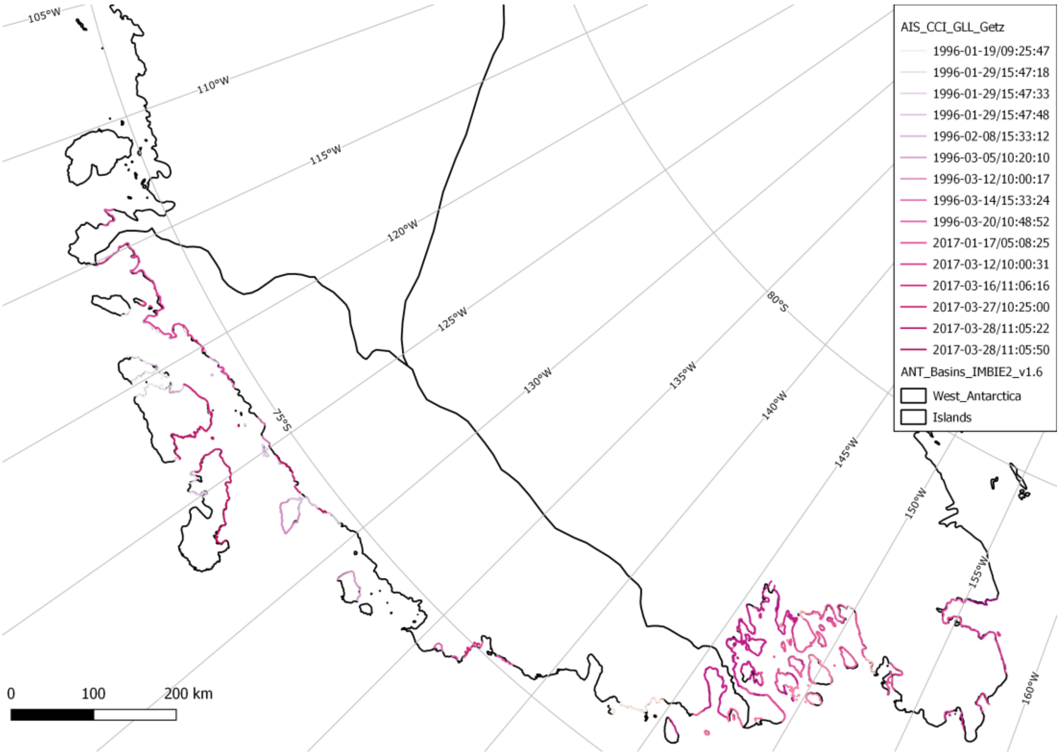


Figure 9. *Grounding Line Location products for the Getz (a) and Sulzberger (b) study areas in west Antarctica, generated from SAR data acquired between 1996 and 2017.*

The effectiveness of the algorithms used to derive this product, can be measured in terms of the fraction of this portion of Antarctic grounding line where a grounding line position has been derived. For this study area, there is now an extremely comprehensive and detailed GLL dataset available along the Sulzberger coastline, however larger data gaps still exist along the Getz sector. On consultation with the AIS_cci GLL team we established that this was in large part not due to the data processing, but due to a hold up in the delivery of some historical ERS data that had been requested from the ESA ground segment, which was not delivered in time for this assessment.

A detailed investigation of the GLL product shows difference, possibly, changes in the grounding line of the eastern Getz Ice Shelf during the 20-year period of observation (1996 – 2017). Elsewhere, the location of the grounding line, wherever multiple observations are available appear to be rather precisely coincident. Certainly, to the level expected, when the likely sources of noise and error are considered.

4.3 Recommendations for IV and GLL product improvement

The major recommendation for the IV and GLL datasets are simply to extend the spatial and temporal coverage of both datasets in year 3 of the AIS_cci projects. The product formats and metadata provided are clear and very user friendly, however the only thing limiting the usefulness of these data sets is the data gaps that still exist. As it will never be possible to fill all of these gaps with observations alone, we recommend that ESA pursue a data assimilation approach which would allow the observations to be used in combination with ice flow models to produce the most spatially complete and time varying estimate of ice velocity and grounding line location for Antarctica, optimising the usefulness and exploitation of these valuable EO datasets. Given the data gaps present in both the IV and GLL datasets for the present day observations, we recommend that Sentinel-1 data is acquired with the shortest repeat period possible (6-days rather than 12-days), and this will aid measurement retrieval.

5 Using AIS_cci data to improve our understanding of the Getz & Sulzberger Sector, West Antarctica

Four Essential Climate Variable datasets generated from the AIS_cci project have been used to observe surface elevation change, mass balance, grounding line location and ice velocity in the Getz and Sulzberger sector (Basin 20) of West Antarctica. We now use all 4 datasets to explore what processes may be responsible for the glaciological change observed.

As discussed in section 4, the utility of the ice velocity datasets is limited by the large data gaps that exist in each datasets. To evaluate change in ice speed over time we employed the BICICLES ice flow model to generate an optimised ice velocity product for the whole of basin 20. The methodology for this is fully described in Hogg et al, (2017) and using the MEASURES velocity map as the earliest ice speed estimate (the full time series of AIS_cci IV measurements were not yet available when this analysis was performed), and the Sentinel-1 IV map for the later estimate. We then used this data to generate an optimised ice flow map for the mid 2000's and the 2016/7 period (Figure 10). This procedure not only enables a spatially complete ice velocity map to be generated from the AIS_cci datasets, but shows that the IV product is delivered to the community in a useful format that is compatible for use with ice flow models.

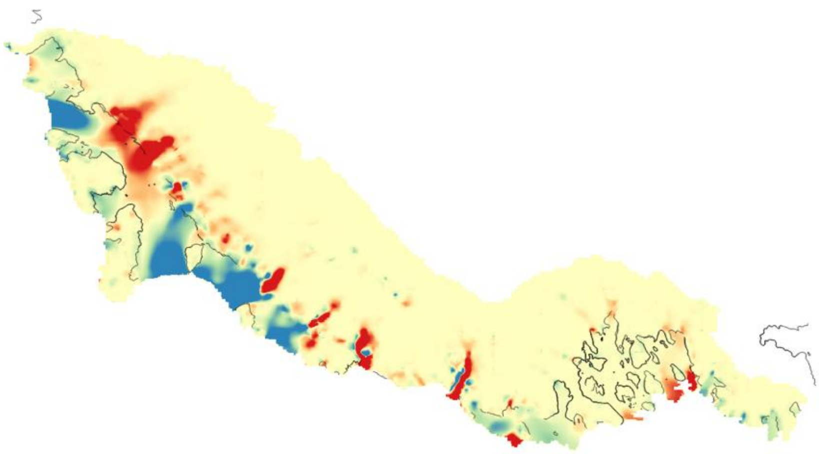


Figure 10. *Optimised ice velocity difference generated using the BICICLES ice flow model in the Getz and Sulzberger basins, generated from the MEASURES IV dataset and the Sentinel-1 AIS_cci IV data for the 2005 and 2017 time periods respectively.*

We compared the optimised IV with the observed IV result, which showed that the error between the two is normally distributed with no obvious bias, with a total magnitude of < ±0.2 meters per year for the majority of the basin (Figure 11).

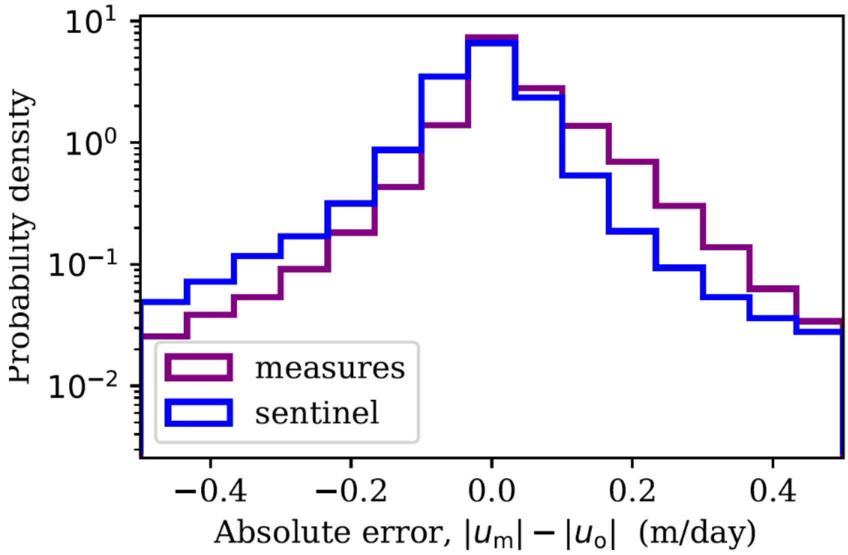


Figure 11. *Difference between the observed and optimised ice velocity measurements generated in the Getz and Sulzberger basins.*

Using the optimised ice velocity datasets we were able to calculate change in ice speed between 2005 and 2017, across the whole basin (Figure 12). When we overlaid the AIS_cci grounding line dataset on the over velocity difference map, we find that on ice streams that have exhibited a large change in speed (> 0.3 meters per year), there is a corresponding change in grounding line position. Where multiple observations of the same grounding line have been achieve, the result in consistent, in that there has been upstream, inland migration of the grounding as is expected from a thinning ice shelf. This result in itself adds credibility to the measurement itself (should that be needed, given the rigour applied to the derivation thereof), and adds to a coherent glaciological interpretation of the area as having increased heat-supply beneath the ice shelf, with consequential ice-shelf thinning and grounding line retreat (Jacobs, 2013).

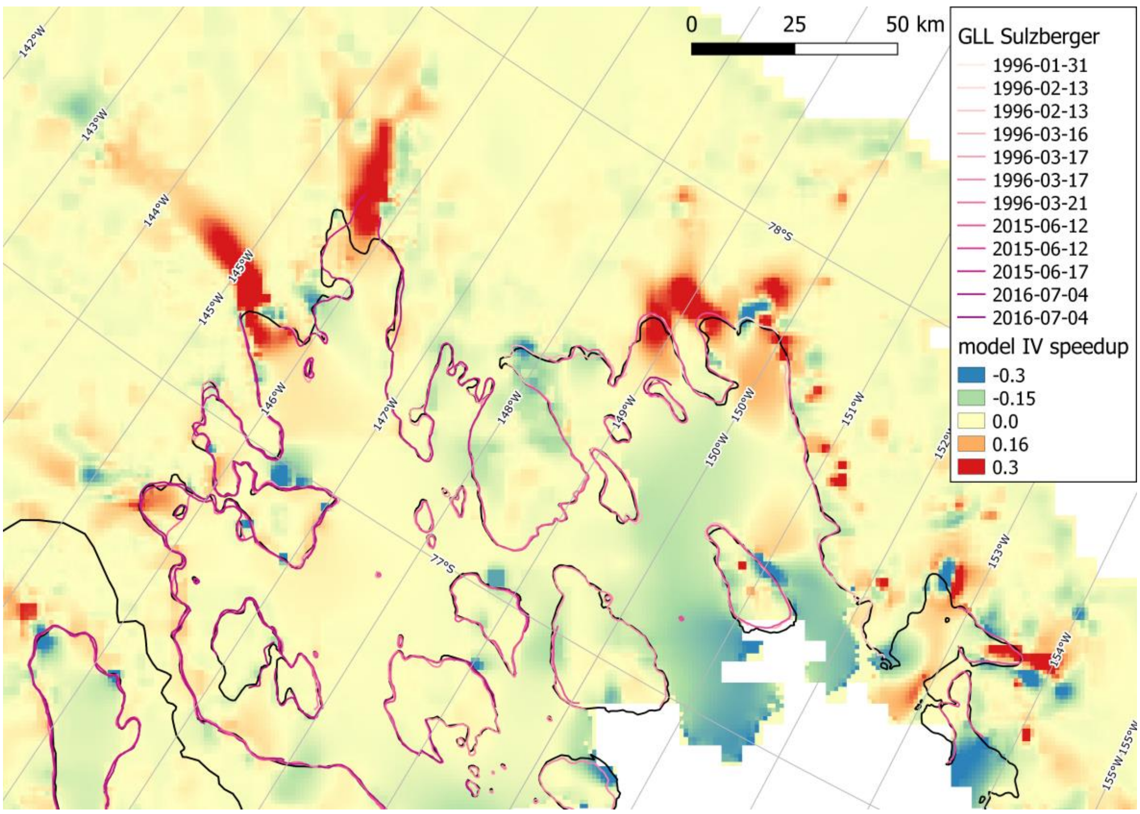


Figure 12. *Change in ice speed calculated from the optimised ice flow measurements generated for 2005*

and 2017 in the Sulzberger basin (red blue colour scale). The AIS_cci grounding line data product is also overlaid, illustrating the comprehensive coverage of this product for 1996 (light purple) and 2015/7 (dark purple).

Dynamic instability, primarily driven by ocean forcing, has been observed to cause grounding line retreat, ice velocity speedup and rapid ice sheet thinning on large fast flowing ice streams elsewhere in Antarctica, such as Pine Island Glacier. Therefore, we examined the surface elevation change dataset to see if a thinning signal was detected in Sulzberger to correspond with the regions of ice velocity speedup and inland migration of the grounding line (Figure 13).In the Sulzberger region we find that the 5 km SEC grid resolution is too coarse resolution to intercompare robustly with the ice velocity difference and grounding line retreat map, however there do appear to be some regions of thinning that may correspond to the regions of ice speedup. There would be clear value in generating a surface elevation change map from higher resolution (~0.5km x 0.gkm grid) swath mode radar altimetry which is available during the CryoSat-2 period.

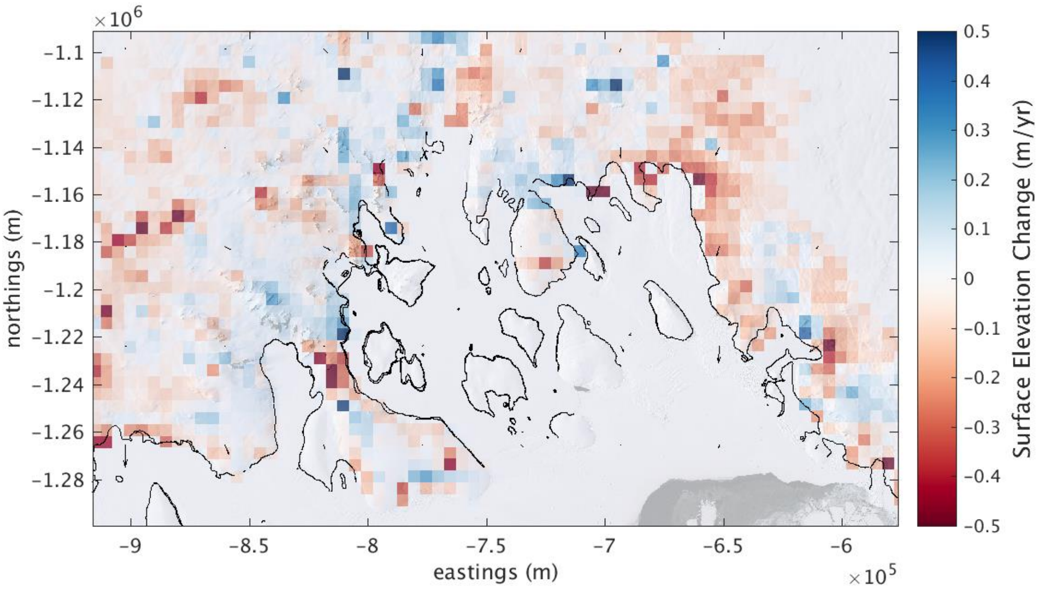


Figure 13. *Close up of the surface elevation change measured by radar altimeter satellites in the Sulzberger basin of west Antarctica (red blue colour scale). The grounding line location (black solid line) is also annotated, and the Landsat mosaic of Antarctica (LIMA) is used as the background image.*

When we use the BICICLES ice flow model to project how future grounding line retreat will manifest itself in the Sulzberger region of Antarctica (Figure 14), we can see that the ice streams with the largest grounding line retreat correspond to the locations with the largest observed retreat (Figure 13).

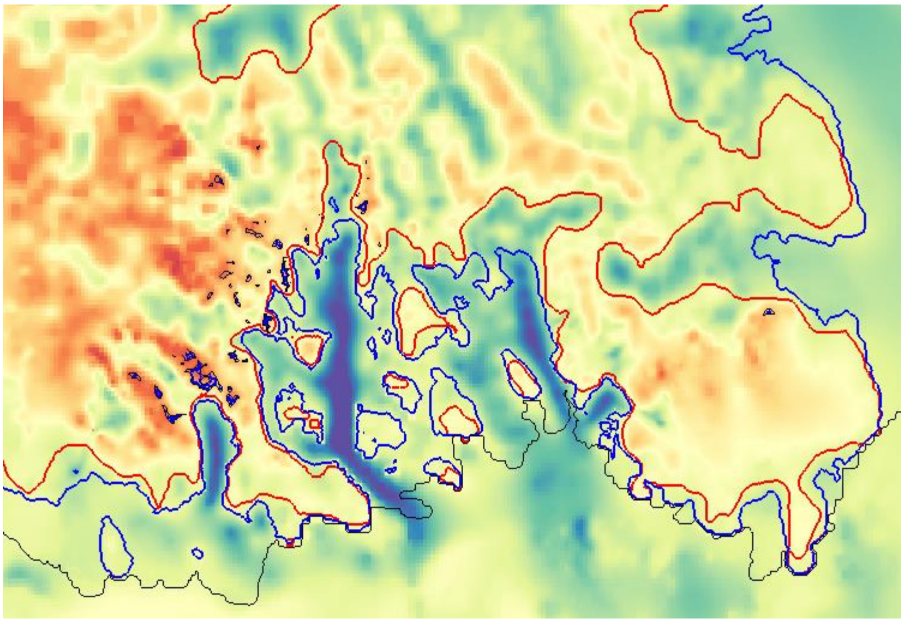


Figure 14. *Model projection of grounding line retreat in the Sulzberger sector of Antarctica. Background colour is the BEDMAP2 bedrock elevation where regions located below present da sea level are highlighted in cold colours (blues and greens), and bedrock above present day sea level is represented by warm colours (orange. The present day grounding line location (blue line) and modelled projectedfuture grounding line (red line) are also annotated.*

For the whole Getz and Sulzberger basin we extracted the ice geometry (surface height and thickness) along the grounding line of the drainage basin (Figure 15a).We extracted the elevation change and ice speed along this same flux gate to establish if regions of fast flow correspond to the regions of most rapid thinning (Figure 15b). If present this relationship that may be indicative of dynamic instability, which might be implied by the absence of any change in surface mass input into the basin over the 25 year epoch (Figure 4). The results show that in the Getz sector (0 to ~1200 km along the gate), as the elevation change becomes more negative (<~-1 m/yr), the ice speed is faster (~>400 m/yr). This region also corresponds with the ice grounded most deeply below present day sea level (>~-450 m), which is therefore most likely to come into contact with the warmest ocean water which is found at depth. These results may therefore indicate that dynamic instability is partially responsible for driving the observed ice mass loss in this region of Antarctica.

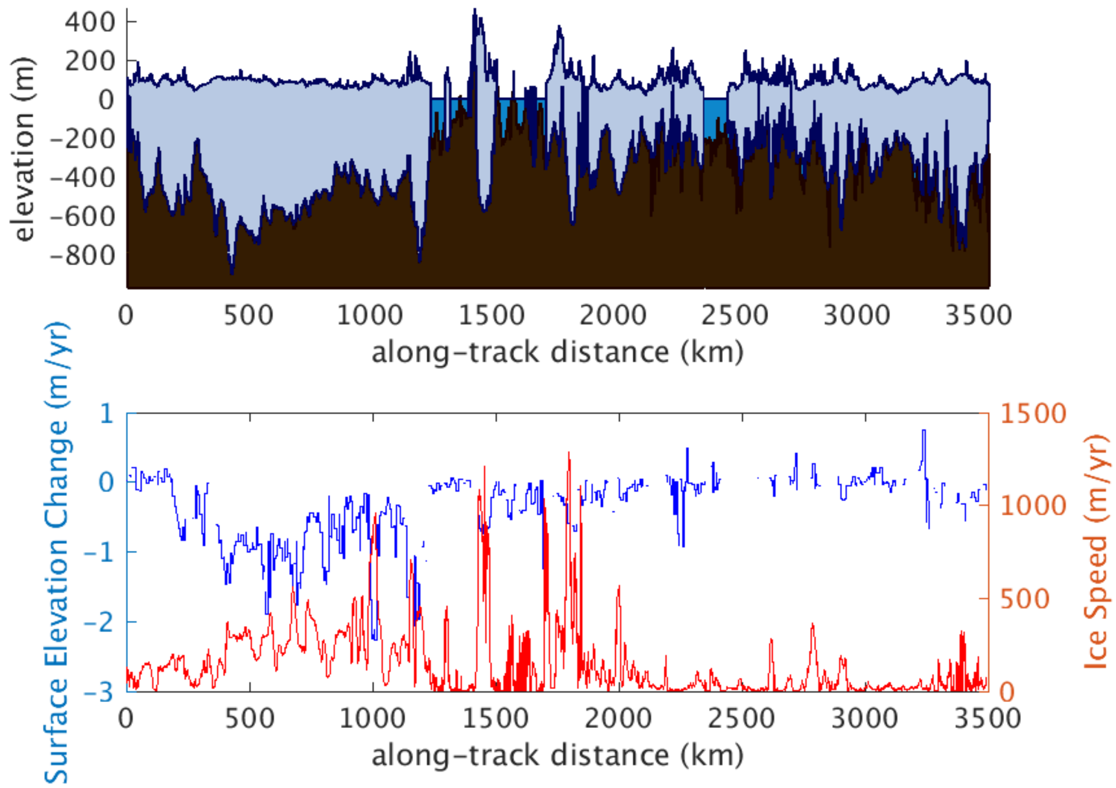


Figure 15. *The top panel (a) shows the geometry of the Getz and Sulzberger basin along the ice sheet grounding line, with ice surface and base (dark blue line and light blue shading), and bedrock elevation (brown) annotated. The bottom panel (b) illustrates the surface elevation change (blue line) and ice speed (red line) along the same discharge gate. The transect is located along the Getz basin grounding line (black line in figure 9), where 0 km is located at the Amundsen Sea end of the basin, and 3500 km is the boundary adjacent to the Ross ice shelf.*

Although preliminary in nature, this climate assessment report shows that the glaciological datasets generated by the Antarctic CCI project are clearly informative, and useful for a range of scientific applications. We have demonstrated how the EO data can be incorporated into ice flow models to provide a complimentary insight into the environmental change in this lesser studied region of Antarctica. Although the Sulzberger area is not the most rapidly changing region of Antarctica, the level of detail provided by the AIS_cci datasets perhaps allows us to evaluate environmental change at a level of detail not previously possible. There was large value in completing the climate assessment report as a regional study and we would suggest the same approach could be taken for next years study.

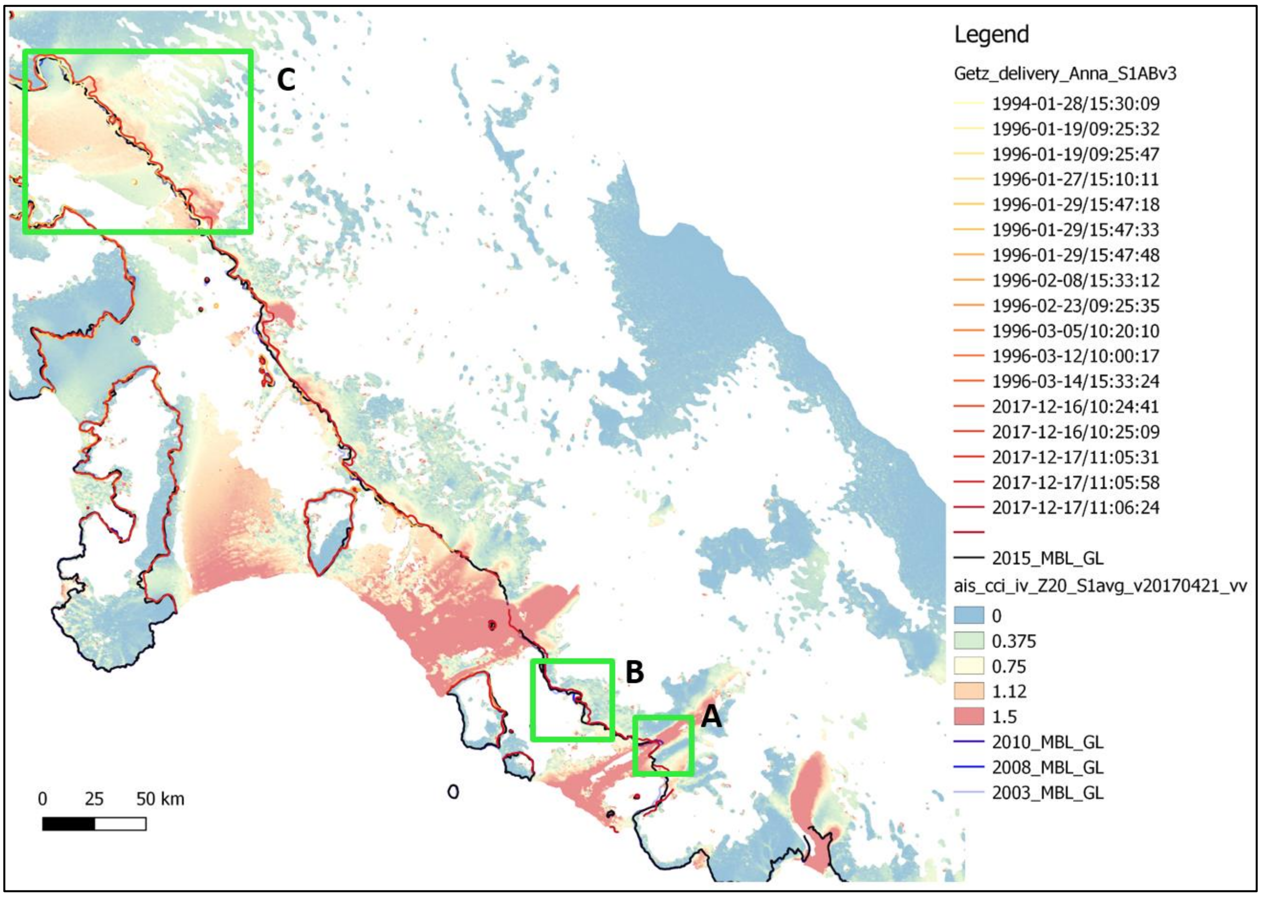
6 Discussion of AIS_cci results in the context of other published literature

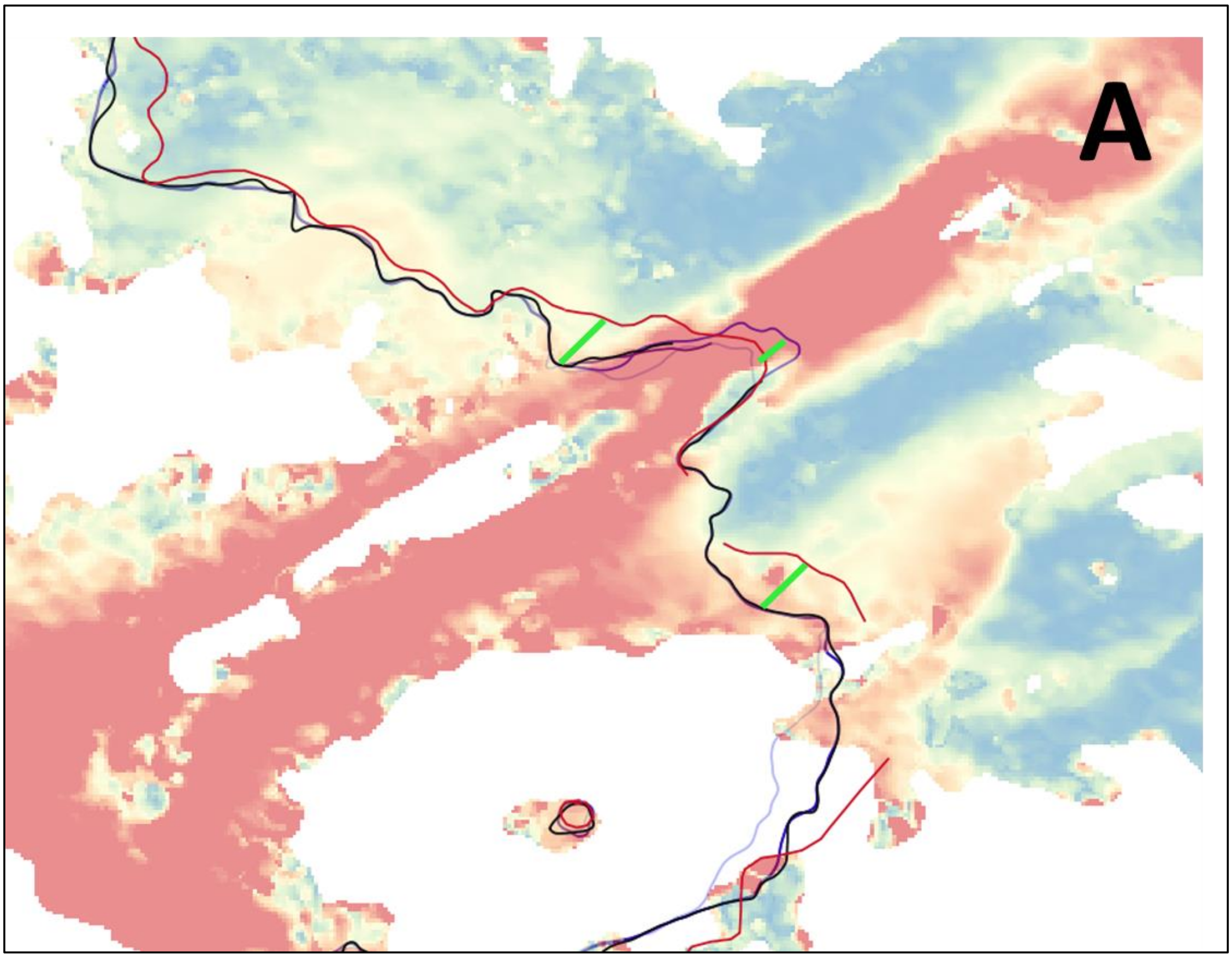
In this section we present the results of the Year 3 climate assessment report for the Antarctic Ice Sheet CCI project. Here we provide an assessment of some selected CCI datasets against Earth observation products generated by other projects (e.g. NASA Measures), or in publications. We focus on the grounding line and ice velocity dataset because they are scientifically interesting in the Getz region where this assessment is carried out.

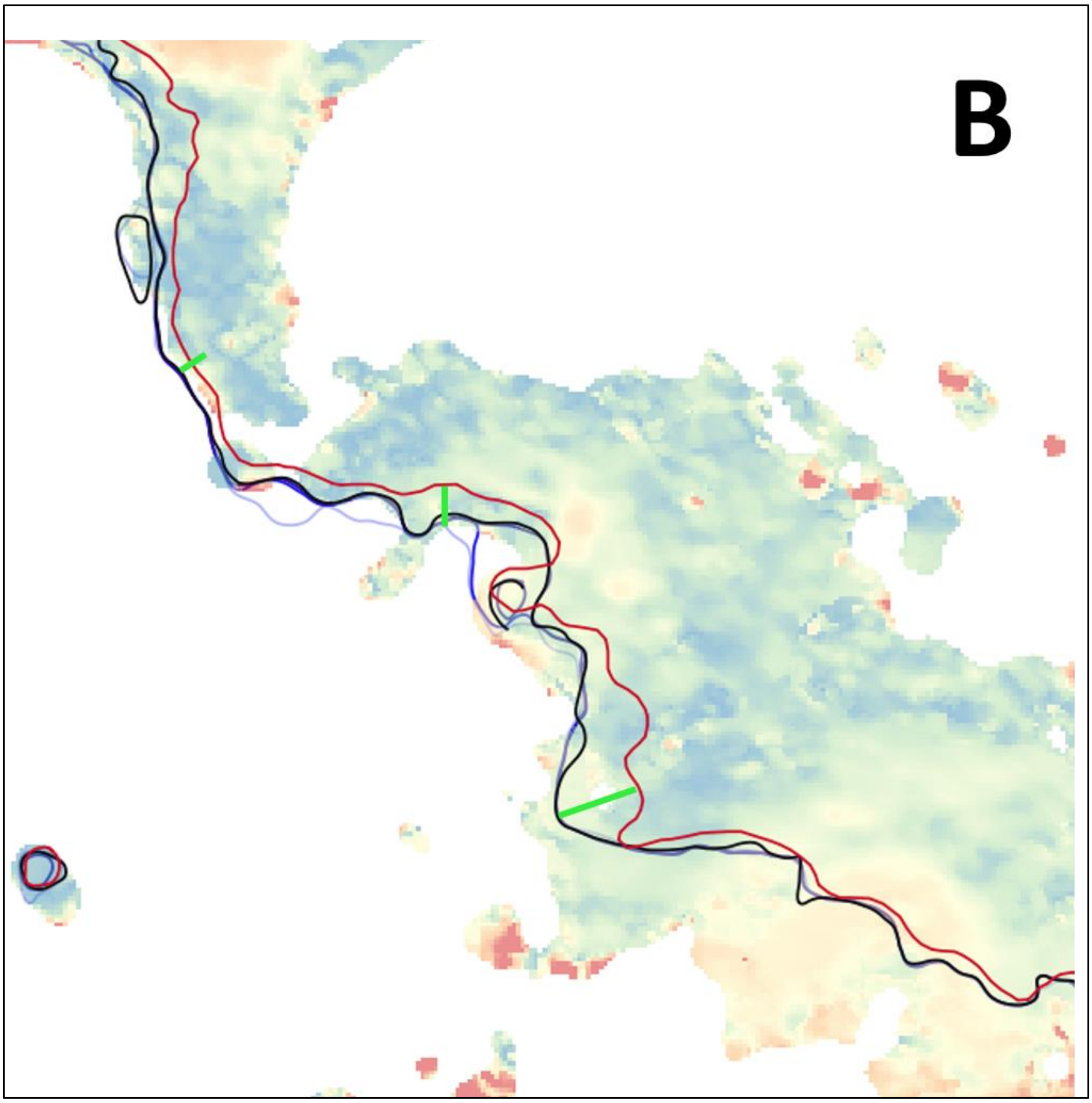
6.1 GLL

Ice sheet grounding lines mark the boundary between the floating ice shelf and the grounded ice sheet. They are a sensitive indicator of ice sheet stability because change in position indicates the presence of an ocean forcing mechanism, and inland retreat affects the flow of grounded ice due to unbuttressing. When grounding line retreat is initiated on ice streams with a retrograde bedrock slope, this may trigger unstoppable 'marine ice sheet instability', the source of extreme sea level rise projections.

Here we compare a time series of grounding line positions measured by the Antarctic Ice Sheet Climate Change Initiative team using a combination of SAR datasets acquired by ERS-1/2 and Sentinel-1, and processed using quadruple difference interferometery. This was compared against an independently generated grounding line position produced by manual delineation of the break in surface slope which is visible in multispectral optical data, and generated by an external team not involved in the CCI programme. The grounding lines measured by the CCI project team covers two major time periods, 1996, and 2017. The grounding line dataset generated by the external project team from optical data covers 4 different epochs, 2003, 2008, 2010, and 2015. Therefore although the datasets are not precisely coincident in time, they do overlap the in time so a comparison is justified on this basis. Figure 16 shows an overview map of a large portion of the Getz drainage basin grounding line. In the background the Sentinel-1 ice velocity map of the region is also shown. The AIS_cci project grounding lines are shown in 'hot' red colours, and the auxiliary optical grounding lines are shown in 'cold' blue colours. The three sub regions 'a', 'b' and 'c' are shown on the main map, and then zoomed in in the panels below.


C
B
A
0 25 50 km
Legend
Getz_delivery_Anna_S1ABv3
1994-01-28/15:30:09
1996-01-19/09:25:32
1996-01-19/09:25:47
1996-01-27/15:10:11
1996-01-29/15:47:18
1996-01-29/15:47:33
1996-01-29/15:47:48
1996-02-08/15:33:12
1996-02-23/09:25:35
1996-03-05/10:20:10
1996-03-12/10:00:17
1996-03-14/15:33:24
2017-12-16/10:24:41
2017-12-16/10:25:09
2017-12-17/11:05:31
2017-12-17/11:05:58
2017-12-17/11:06:24
2015_MBL_GL
ais_cci_iv_Z20_S1avg_v20170421_vv
0
0.375
0.75
1.12
1.5
2010_MBL_GL
2008_MBL_GL
2003_MBL_GL


A


B

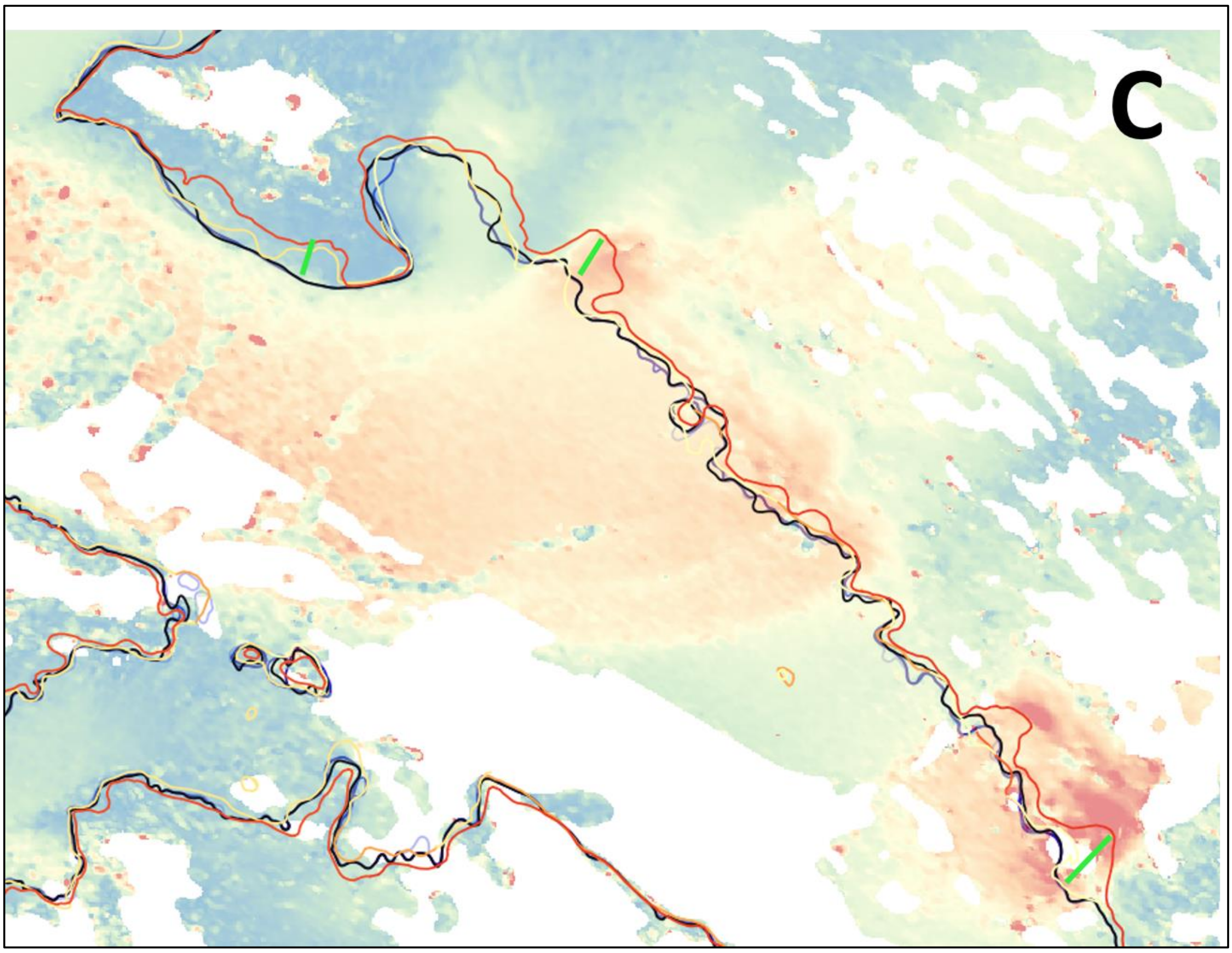


Figure 16. *A large map of the grounding line in the Getz drainage basin, where the AIS_cci grounding line product is shown in 'hot' red colours, and an auxiliary optical grounding line product is shown as blue lines. The Sentinel-1 ice velocity map produced by the AIS_cci project team is also shown in the background. On the sub maps of zoomed in regions, the locations at which difference in grounding line positions were measured are shown as thick green lines, located in the flow line direction.*

The sub regions shown in Figure a, represent different glaciological aspects of the Getz grounding zone. Study region 'A' is a relatively narrow fast flowing ice stream, region 'B' is a very slow flowing apparently inert part of the coastline, and region 'C' is a fastish flowing but unconstrained set of glaciers that are also observed to be thinning rapidly relative to other parts of this coastline in the AIS_cci surface elevation change datasets. Table 3 (below) shows the difference in the grounding line position at 3 locations in each sub region, at locations identified by a green line in Figure 16.

Table 3. *Difference in the grounding line position between an auxiliary grounding line dataset generated from optical break in surface slope, and the interferometric grounding line product generated by the Antarctic Ice Sheet CCI team. Differences in position are measured in 3 glaciologically different sections of the Getz coastline (A, B, and C shown in Figure 16), where differences 1, 2, and 3 are measured at the locations where the green line is marked on each*

subsection.

Area of Interest	GLL difference 1	GLL difference 2	GLL difference 3
A	-3.3 km	+1.5 km	-3.5 km
B	-0.8 km	-1.3 km	-3.5 km
C	-4.7 km	-5.8 km	-8.2 km

In all 3 sites the AIS_cci interferometrically derived grounding line product is generally further inland than the optical break in slope product. The main region where this broad theme doesn't hold is in the fastest flowing section of the glacier shown in section 'A', where the optical grounding line is 1.5 km further inland than the interferometric AIS_cci product. Overall this suggests that the optical technique may systematically underestimate the true grounding line position. In region 'C' which is the site observed to be thinning most rapidly in the SEC data, this region shows the greatest difference between the two products, with the optical dataset misplacing the grounding line over 5km more seaward than its true position in all locations measured. This suggests that the optical technique may not be well suited to mapping grounding line position in rapidly changing regions of the coastline. Its interesting to note that in site 'C' location '1', the optical grounding line product places the grounding line position seaward of even the 1996 interferometric product, suggesting that there are some regions where the break in surface slope may not correspond to the true limit of tidal displacement. It will be interesting to investigate these differences in grounding line position in more detail in the future.

6.2 IV

Ice velocity measurements are an important glaciological parameter which can be used to better understand the physical processes responsible for driving fluctuations in the ice sheet contribution to sea level rise. Regional meteorology controls the mass accumulated at the ice surface through precipitation, snow and ice melting, refreezing, and sublimation. Alternatively change in ice flow, otherwise known as 'ice dynamics', controls the rate at which ice mass is discharged into the ocean, either as icebergs or through basal melting of marine terminating glaciers and ice shelves. Change in ice sheet elevation can be caused by both surface mass anomalies and ice dynamics. Reduced accumulation across a drainage sector leads to surface lowering over short timescales, and this is compensated over time as the ice flow slows down due to reduced driving stress. Alternatively, if there is a relative difference in ice speedup along the glacier with faster flow occurring downstream, the ice will be stretched and surface lowering will also ensue. Because ice sheet surface lowering arising through surface mass or dynamical imbalance has an opposing effect on the rate of ice flow, the origin can be established by measuring trends in ice speed. In addition to this, changes in ice flow can also be an indicator of marine ice sheet instability, where mass loss leads to a positive feedback mechanism, such as the case of grounding line retreat on a retrograde bedrock slope in the absence of a compensating mechanism.

While the short-term weather anomalies responsible for meteorological imbalance are relatively well constrained, dynamic imbalance *and* instability is oceanographic in origin and the environmental conditions responsible for triggering it are less well understood. As a result, the Antarctic Ice Sheet remains the largest uncertainty in estimates of sea level rise this century due to lack of understanding about the what environmental conditions drive dynamic imbalance and marine ice sheet instability, the only mechanism through which extreme sea level rise (>1 m) can occur. As such, generating ice velocity measurements from the Antarctic Ice Sheet CCI project continues to be of critical importance.

For this climate assessment report we also examined how the CCI project ice velocity measurements compare with results generated by different methods within the CCI project team, and we then compared this to externally generated results to see if a change in ice speed can be detected by the CCI datasets. Figure 17 shows an ice velocity map generated from a combination of intensity feature tracking and interferometry, based on data acquired by ERS-1/2 during the 1995/6 tandem phase. This is compared to an ice velocity map generated by the University of Leeds that shows speed measured using intensity feature tracking of visible features between a single pair of 12-day repeat Sentinel-1 images acquired in 2015. While there is sparser data coverage in the Sentinel-1 dataset this is due to the fact that it is not a merged product built up from multiple SAR acquisitions.

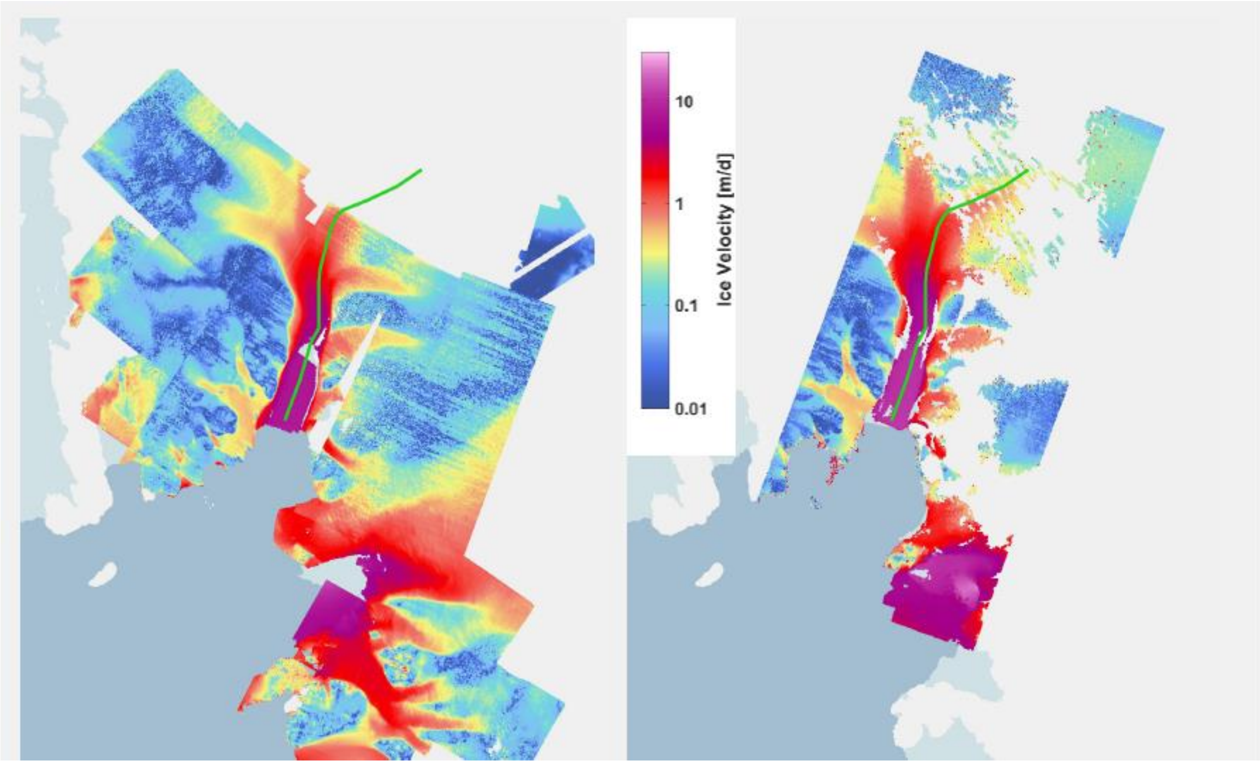


Figure 17. *The panel on the left shows an ice velocity map of Pine Island Glacier in West Antarctica generated from ERS-1/2 data acquired in 1995/6, and processed using a combination of tandem interferometry and feature tracking. The image on the right hand side shows an ice velocity map also of Pine Island Glacier generated from a single 12-day pair of Sentinel-1 SAR images, processed using intensity feature tracking. A flow line up the central trunk of the glacier is shown as a green line.*

We extracted a transect of ice velocity measurements from each of the datasets shown in figure 17, and also a NASA MEASURES velocity dataset with a 1996 timestamp, and a second 2015 ice velocity dataset generated by the DTU team responsible for the ERS measurements shown in Figure 17. These results, shown in Figure 18, show firstly that between 1996 and 2015/17, there was a large velocity speedup, just less than 50% of the total ice speed. This result is in agreement with the peer reviewed literature (Mouginot et al, 2014) which showed large speed up of this glacier. This demonstrates that the Antarctic Ice Sheet CCI ice velocity data products are capable of measuring change in ice speed of large Antarctic ice streams. Figure 18 also reveals that there is extremely close agreement between (i) CCI project ice velocity measurements processed by different teams in the project (e.g. 2017 (UoL), and 2015 (DTU)), and also close agreement between CCI datasets generated by the project compared externally generated results (e.g. 1996 (DTU) and 1996 (Mouginot et al, 2014). This aspect of the year 3 climate assessment demonstrates that the CCI ice velocity datasets generated within the project are internally consistent even if generated using different techniques; are able to measure real change in ice speed; and compare very well to comparable results generate by other scientists external to this project.

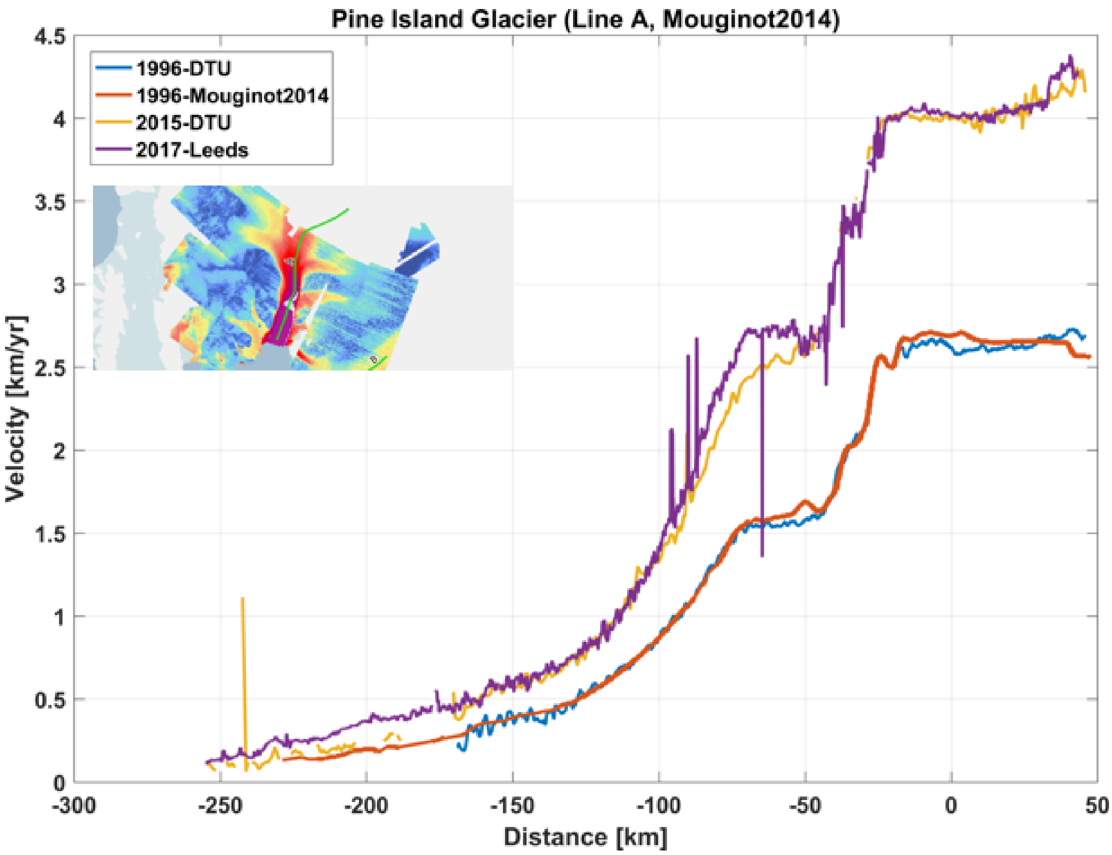


Figure 18. *Ice velocity measurements extracted from 4 independently produced datasets along a flow line transect located along the central fast flowing trunk of Pine Island Glacier, as shown in figure 17 above.*

6.3 Year 3 climate assessment recommendations

The following list of recommendations has been made following the year 3 climate assessment performed for the Antarctic Ice Sheet Climate Change initiative. These recommendations were presented to ESA at the final project meeting held in ESRIN in July 2018.

- In the future satellite data products required to feed into large new international science projects:
    - E.g. UK(NERC) & USA (NSF) joint Thwaites Glacier, German/European Mosaic
- While individual research projects might provide an interesting study of a small study area, there is still a scientific need for large continent wide data products to be generated
    - The CCI played a valuable role in funding European capability in this area over the last 6 years, and this should not be lost in the future

- The cci set new standards for satellite data product record length, method documentation, processor automation, uncertainty characterisation
    - Interlinked CCI community of multidisciplinary EO experts – lessons learnt from different thematic areas
    - This has not been translated into public or educational outreach materials, so an opportunity for the future to better exploit this. Will raise awareness of CCI outside of the project teams.
- Multidisciplinary, cross-ECV activities have only just come to fruition now long term data records are available from multiple ECV's
    - SLBC_cci is good first example, but more needed to fully capitalise on CCI investment
- Extremely difficult to fully engage the CRG in doing the climate assessment
    - Financial remuneration doesn't cover the time required for the work
    - Suggest ask for one peer review publication to come out of the full 3 year period, rather than an annual document – if good science can be done with the data, that says it all!

Appendix A Document Description and CRG Technical Note

Document description in accordance to Statement of Work (SoW).

D5.1.X Climate Assessment Report (CAR)

The Climate Assessment Report describes:

- The feedback of users on the delivered AIS_cci data products in respect to the behaviour globally and regionally of the time series of AIS_cci data.
- A comparison against other Antarctic Ice Sheet related initiatives (EC, ESA, National, Global).
- The comparison against outputs from other ECV projects.

For ECVs where models are used:

- Assessment of the contribution to the improvement of model performance with reference to the representation of observations based on the current climate.
- The approaches used to introduce the ECV products in to the models.
- Any required model developments.
- Where changes in the model have been made: the impact of such changes on the model outputs.
- Comparison of the model with and without the ECV product/results.
- The comprehensive error analysis derived through confrontation of the models and ECV products taking into account the inherent errors and uncertainty expressed in the URD, PSD and PVIR.

Written by: engaged Climate Research Group

Commented by: CMUG and the other related ECV producers, EO Science Team

Formally reviewed by: submission to internationally recognized peer-reviewed scientific journal.

CRG Technical Note

Antarctic Ice Sheet Climate Change Initiative

Technical note on Climate Research Assessment

Date: 8th September 2015

Author: Andrew Shepherd

Applicable Documents: CCI Phase II SoW, AIS CCI Proposal

List of Acronyms	
Statement of Work	SoW
Climate Change Initiative	CCI
Climate Research Group	CRG
Antarctic Ice Sheet	AIS
Essential Climate Variable	ECV
Climate Modelling User Group	CMUG

Intergovernmental Panel on Climate Change	IPCC
Assessment Report	AR
Coupled Model Inter-comparison Project	CMIP

[1] The purpose of this technical note is to clarify how data products emerging from the Antarctic Ice Sheet Climate Change Initiative project will be assessed in the context of climate research.

[2] During CCI Phase I, the role of the CRG was to identify user needs, provide independent critical review of algorithms and data products, and to assess the consistency of data products. In CCI Phase II, the objective of the CRG is to maximise the impact of CCI data products.

[3] With this in mind, in CCI Phase II the specific activities of the CRG include assessment of data products for climate research, identifying how the work will be coupled with international assessments, providing feedback to the consortium on the added value of the data products, organising user workshops to assess the data products, liaising with international assessments, supporting CMUG activities on climate modelling, and participating in CMUG meetings.

[4] In order to meet these requirements, in CCI Phase II the Ice Sheets CCI CRG was reformed to include key international scientists in Greenland and Antarctic ice sheet research under the leadership of Professor David Vaughan, a world renowned glaciologist and co-ordinating lead author of the fourth and fifth IPCC Assessment Reports. Other members of the AIS CRG are Michiel van den Broeke with expertise in polar meteorology, Hartmut Hellmer with expertise in modelling ice-ocean interactions, Anne le Broq with expertise in ice sheet modelling, and Ernst Schrama with expertise in satellite gravimetry.

[5] In the AIS CCI proposal, the planned activities of the AIS CRG were to inspect the quality of the ECV's produced using a series of experiments, to compare the ECV's to alternative products, and to assess their uptake by the user community.

[6] Following discussions at the first progress meeting of the AIS CCI, it was agreed to supplement these proposed activities with additional work to ensure compliance with the objectives of CCI Phase II. The additional work will address how the AIS CCI work will be coupled with international ice sheet modelling assessments.

[7] It should be noted that ice sheet models were not included in the deck of CMIP experiments carried out in support of IPCC AR5. One consequence of this omission is that AR5 global sea level projections based on rapid ice sheet dynamical imbalance are considered to be unrealistically low. The omission also presents an obstacle to immediate uptake of AIS CCI data products within international assessments, because they historically have not existed within the IPCC framework. Nevertheless, the Ice Sheets CCI CRG Lead was coordinator of the only international ice sheet modelling assessment to date – the EU Ice2Sea project – and the AIS CCI CRG members lead state of the art ice sheet modelling activities outside of the IPCC framework, which we will utilise to exploit the AIS CCI data sets.

[8] The AIS CCI will perform the following new modelling activities utilising CCI data products:

- Using CCI ice velocity data for ice sheet model initialisation. Ice velocity maps will be used to invert for basal boundary conditions, and ice velocity time series will be used to test the suitability of ECV data for detecting changes in basal conditions – especially in the vicinity of the grounding line.
- Using CCI ice sheet grounding line positions as ice sheet model initialisation.

- Using CCI ice elevation change data for ice sheet model initialisation. Maps of elevation change will be used to constrain historical environmental forcing and future scenarios, specifically changes in thickness at the ice sheet margin as a measure of ice shelf basal melting.
- Using CCI sea surface temperature data, where available, as an additional constraint on historical forcing and future scenarios.
- Using CCI ice elevation change data to evaluate the performance of ice sheet model projections.
- Using CCI ice sheet grounding line retreat data to evaluate the performance of ice sheet model projections.
- Using CCI ice sheet gravimetry mass balance data to evaluate the performance of ice sheet model projections.

[9] In addition to these activities, it will become possible to engage directly with IPCC in the future because an ice sheet modelling activity – the Ice Sheet Model Inter-comparison for CMIP6 (ISMIP6) - has been initiated in support of AR6. The AIS CCI Lead is a member of the ISMIP6 steering committee, and is involved in the design of the CMIP6 experiments themselves. To fully engage with the project, we recommend contracting a specific set of work involving CCI data products to ice sheet modellers capable of participating in the CMIP6 deck of experiments, through the CCI CMUG. Professor Phillipe Huybrechts and Professor Frank Pattyn are capable of fulfilling these roles for the GrIS and AIS CCI projects, respectively.