Product Specification Document (PSD) Phase 2 Year 3

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Contents

1. Introduction

1.1 Document purpose and scope

This document outlines the specifications of the products that are to be generated during Phase 2 of the Glaciers_cci project. The document builds on the information supplied in the PSD from Phase 1. Any updates to the Phase 1 specifications are based on the Phase 2 assessment of the user requirements and the data access as outlined in the User Requirements Document (URD) and the Data Access Requirements Document (DARD), as well as the core project requirements provided by ESA. Specifically, the document presents an assessment of the required key regions for study in Phase 2, and the specifications and formats of each of the products – namely Glacier Outlines (GO), Surface Elevation Change (SEC) from altimetry and DEM differencing, and Ice Velocity (IV). The PSD will be an essential reference for product generation throughout Phase 2 of the Glaciers_cci project.

1.2 Document structure

The document is structured as follows:

- Chapter 2 provides an assessment of the key regions for study in Phase 2 of the Glaciers_cci project.
- Chapter 3 outlines the product specifications, based on the outcomes of the URD and the DARD, for GO, SEC altimetry, SEC DEM differencing and IV.
- Chapter 4 provides a synthesis of the anticipated spatial and temporal coverage of the different products.
- Chapter 5 summarises the format in which the GO, SEC altimetry, SEC DEM Differencing and IV products will be delivered.

1.3 Relevant Documents

We refer to the following relevant documents in this report:

[RD1]	Glaciers_cci- D1.1-URD-Ph2Yr1
[RD2]	Glaciers_cci-D1.4_DARD-Ph2Yr1
[RD3]	Annex I: Glaciers and Ice Caps ECV (Glaciers_cci), CCI-PRGM-EOPS-SW-12-0012

2. Key regions for study

This section identifies the key regions for which products will be generated in Phase 2 of the Glaciers_cci project. We outline the assessment leading to their selection which is based on the outcomes of Phase 1 of the project, a review of recently published results, and reviews of the user requirements and data access as presented in the Phase 2 URD [RD1] and DARD [RD2]. The 19 first-order regions of the RGI are used for spatial differentiation and are illustrated in Fig. 2.1.

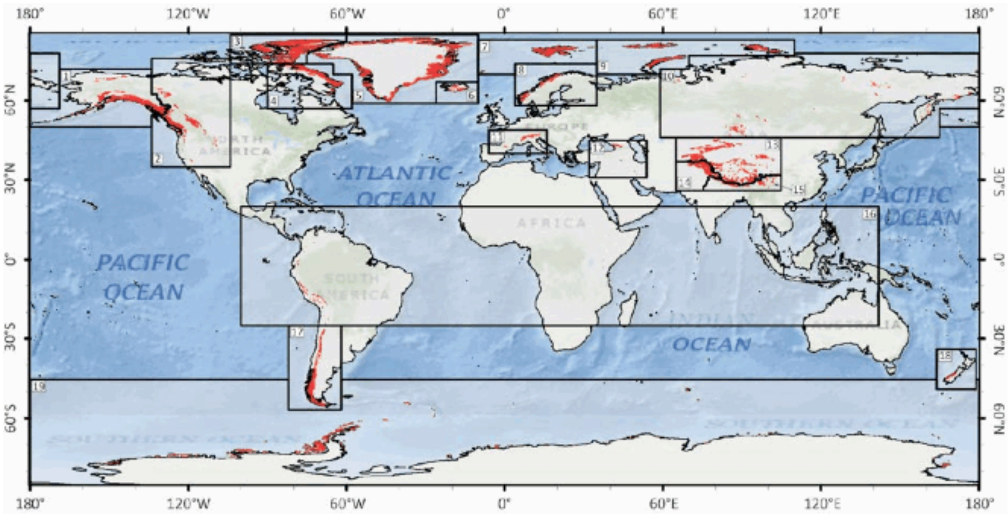


Fig. 2.1: Overview of the first-order RGI regions (from Pfeffer et al. 2014).

2.1 Phase 1 regions of study

Data products had already been created for several regions in Phase 1 of the project. They are described in detail in the CRDP document of Phase 1 (Glaciers_cci, 2014) and are thus only briefly summarized in Table 2.1 for completeness. The main focus was on the glacier area product and the timely contribution to the RGI.

Nr.	Region	Products	Nr.	Region	Products
1	Alaska		11	Central Europe	RGI
2	RockyMts		12	Caucasus	
3	Arctic Can N		13	Central Asia (Pamir)	RGI, SEC-ALT, SEC-DEM, IV
4	Arctic Can S	RGI	14	South Asia W	RGI, IV
5	Greenland	RGI, SEC-ALT	15	South Asia E	
6	Iceland	VAL	16	Low Latitudes	RGI
7	Svalbard	RGI, VAL	17	Southern Andes	RGI
8	Norway	RGI	18	New Zealand	RGI, SEC-DEM
9	Russian Arctic		19	Subantarctic isl.	RGI
10	North Asia				

Table 2.1: Overview of products created in Phase 1 in different regions (see Fig. 2.1 for Nr reference). RGI: contribution to the RGI, SEC-ALT / SEC-DEM: surface elevation change from altimetry / DEM differencing, IV: ice velocity (from both optical and microwave sensors), VAL: used as a validation site.

2.2 Review of published regional results

Over the three years of Phase 1 (2012-2014) several studies were published presenting new results for GO, SEC and IV over glaciers and ice caps. To avoid overlap in data production and to identify time periods not covered so far, an up-to-date overview of the most relevant recent work is required and provided in Table 2.2. This table is updated in each year of the study to include newly published material.

Product	Task	Description	RGI	Reference	Journal
Area	Change	Area and length changes for glaciers in Norway	8	Winsvold 2014	TCD
Area	Change	Glacier retreat in Himalaya / Karakoram from LISSIII	14,15	Bahuguna 2014	CurrSci
Area	Change	Area ch. Tibetan Pl. with Landsat since 1970	13	Wei 2014	AnnGl
Area	Change	Northern Eurasia changes from UGI map & ASTER	10	Khromova 2014	ERL
Area	Change	Area change in Big Naryn Basin (Tien Shan)	13	Hagg 2013	GPC
Area	Change	Area change in Big Naryn Basin (Tien Shan)	13	Kriegel 2013	GPC
Area	Change	Area change in Kodar Mts. (Siberia)	10	Stokes 2013	GPC
Area	Change	Area ch. Quilian Mts from Landsat	13	Tian 2014	AnnGl
Area	Change	Changes in Pakistan from Landsat and ASTER	14	Sarikaya 2013	IJRS
Area	Inventory	RGI overview paper describing the dataset	all	Pfeffer 2014	JGlac
Area	Change	Cordillera Real change with Landsat, ALOS, ASTER	16	Liu 2013	RSE
Area	Change	Cordillera Blanca change with atmosph. correction	16	Burns,Nolin 2014	RSE
Area	Inventory Change	Multitemporal inventory Svalbard	7	Nuth 2013	TC
Area	Change	Area changes 1980-2010 Hindukush Himalaya	13,15	Bajracharya 2015	IJWRD
Area	Change	Area changes 1952-2005 Cariboo Mts., Canada	2	Beedle 2015	TC
Area	Change	Area trends 1975-2010 Cordillera Blanca	16	Duran-Alarcon 2015	JSAES
Area	Change	Pan-Arctic change 1980s-2010s for selected scenes	1,3,5, 8, 9,10	Mernild 2015	DJG
Area	Change	Inventory 1985/2000/2010 for northern Patagonia	17	Paul, Moelg 2014	JGlac
Area	Change	Area change 1962-2006 Sikkim Himalaya	15	Racoviteanu 2015	TC
Area	Change	Area changes for 139 glaciers of SPI (Patagonia)	17	White 2015	AAAR
Area	Change	Area changes 1976-2011 for glaciers in Turkey	12	Yavasli 2015	RSE
Area	Inventory	Multiple inventories for Austria and changes	11	Fischer A. 2015	TC
Area	Inventory	2010 inventory for Switzerland and changes 1973	11	Fischer M. 2015	AAAR
Area	Inventory Change	Multitemporal (1960-2009) inventory France	11	Gardent 2014	GPC
Area	Inventory	Second Chinese Gleacier Inventory	13	Guo 2015	JGlac
Area	Inventory	Inventory for Mongolia	13	Kamp, Pan 2015	GeoAnn
Area	Inventory	New Inventory for entire Alaska	1	Kienholz 2015	JGlac
Area	Inventory	GAMDAM inventory for High Mountain Asia	13-15	Nuimura 2015	TC
Area	Inventory	2005 inventory for Torngat Mts., Canada	4	Way 2014	JGlac
Area	Change	from 1954–2007 Ortles-Cevedale group	11	D'Agata 2014	TAClim
Area	Change	Glacier changes in the Ravi basin 1971–2010/13	15	Chand 2015	GPC
Area	Change	Glacier change Karatal river basin, Kazakhstan	13	Kaldybayev 2016	AnnGlac
Area	Change	Glacier & lake changes Bugyai Kangri, SE Tibet	13	Liu et al. 2016	AnnGlac
Area	Inventory	for SE Qinghai–Tibet Plateau w/ Landsat / PALSAR	13	Ke et al. 2016	JGlac
Area	Inventory	A satellite-derived glacier inventory for North Asia	10	Earl, Gardner '16	AnnGlac
Area	Change	Glacier shrinkage across High Mountain Asia	13-15	Cogley 2016	AnnGlac
Area	Change	circumpolar Arctic & sub-Arctic, 1980s to 2011	Arctic	Mernild 2015	GeogrTS
Area	Change	in E Nepal since 1992 from aerial & ALOS images	15	Ojha et al. 2016	JGlac
Area	Change	in central Chilean & Argentinean Andes 1955–2014	16	Malmros 2016	JGlac
Area	Change	Hohe Tauern using Object-Based Image Analysis	11	Robson 2016	RS
Area	Change	Gl. flow/surge dynamics from animated sat. images	14	Paul 2015	TC
Area	Change	Accelerated shrinkage Ak-Shyirak from 2003–2013	13	Petrakov 2016	SciTotEn

Alt-Alt	Change	Dh/dt Greenland GICs from ICESat for 2003-2008	5	Bolch 2013	GRL
Alt-Alt	Change	Dh/dt of glaciers on Baffin / Bylot Islands, Canadian Arctic from repeat altimetry and ATM for 2003-2011	4	Gardner 2012	TC
Alt-Alt	Change	Dh/dt of glaciers in the Russian High Arctic archiplagos from repeat ICESat altimetry 2003-2008	9	Moholdt 2012	GRL
Alt-Alt	Change	Dh/dt of Greenland and Antarctic peripheral GICs from ICESat for 2003-2008	5, 19	Gardner 2013	Science
Alt-Alt	Change	CryoSat-2 delivers monthly and inter-annual surface elevation change for Arctic ice caps.	3, 7	Gray 2015	TCD
Alt-Alt	Change	Mass changes in Arctic ice caps and glaciers: implications for regionalizing elevation changes	3, 4, 6, 7, 9	Nilsson 2015	TC
Alt-DEM	Change	Early 21st century glacier mass balance over the Pamir-Karakoram-Himalaya	13,14, 15	Kääb 2015	TC
Alt-DEM	Change	Dh/dt Karakoram / Himalaya w/ ICESat 2003-2008	14, 15	Kääb et al. 2012	Nature
Alt-DEM	Change	Eleveation change over Tibet	13	Neckel 2014	ERL
Alt-DEM	Change	Dh/dt of small mountain glaciers in Norway from ICESat and DEMs	8	Treichler & Kääb 2016	TCD
Alt-DEM	Change	Mass balance of Grosser Alteschgletscher from ICESat and DEMs	11	Kropáček 2014	Remote Sensing
Alt-DEM	Change	Mass balance of Alaska glaciers (LiDAR and DEMs)	1	Larsen 2015	GRL
dDEM	Data and Change	DEMs and elevation change for Greenland periphery	5	Korsgaard 2016	Scientific Data
dDEM	Change	Area, volume and mass changes of southeast Vatnajökull ice cap, Iceland, from the Little Ice Age maximum in the late 19th century to 2010	6	Hannesdottir 2015	TC
dDEM	Change	Elevation change from DEM time series, New Zeal.	18	Wang 2015	RS
dDEM	Change	2000-2011 volume change for SPI gl. + velocity	17	Willis 2012	RSE
dDEM	Change	Mass loss in Wrangel Mts. (LIDAR & DEMs)	1	Das & Hock 2014	JGlac
dDEM	Change	Approx. 2000-2010 over Pamir-Karakoram-Himalaya from SRTM and SPOT5 DEMs	14, 15	Gardelle 2013	TC
Vel	Data	Heterogeneity in Karakoram glacier surges		Quincey 2015	JGR
Vel	Data	Glacier velocities from a complete satellite archive: Application to the Pamir–Karakoram–Himalaya	13-15	Dehecq 2015	RSE
Vel	Data	Karakoram (PALSAR, TS-X, ERS-1/2, ASAR)	14	Rankl 2014	TC
Vel	Data	Velocity for Chhota-Shigri from ASTER	15	Tiwari 2014	CurrSci
Vel	Data	Karakoram (PALSAR, TS-X, ERS-1/2, ASAR)	14	Rankl 2014	TC
Vel	Data	Velocity fields for Muztag Ata mountain range	14	Zhou 2013	EnvESc
Vel	Data	Flow speeds + volume loss rates for Cord. Darwin	17	Melkonian 2013	TC
Vel	Data	Vel. of gl in Tuomuer-Khan Tengri range PALSAR	13	Li 2013	GPC
Vel	Data	Vel. of Gangotrigl. from TerraSAR-X	15	Kumar 2013,dto. Saraswat 2013	IJRS
Vel	Data	flow field from ASTER for Tasmangl.	18	Redpath 2013	RSE
Vel	Data	Flow field Aletsch glacier fron TerraSAR-X	11	Schubert 2013	ISPRS
Vel	Data and Change	Several regions from repeat Landsat	var.	Heid and Kääb 2012a,b	RSE, TC
Vel	Data and Change	Alaska from repeat PALSAR	1 1	Burgess 2013a Burgess 2013b	Nature C. GRL
Vel	Data and Change	Glacier dynamics and discharge (1999-2015) for Ellesmere and Axel Heidberg Islands	3,4	Welsey 2016	JGR
Vel	Data and Change	Glacier velocity and thinning, Novoya Zemlya	9	Andreew 2016	RSE
Vel	Data and Change	Dynamics of glaciers in West Kunlun Shan, NW-Tibet from ERS-1/2, PALSAR, TSX, LSAT	13	Yasuda and Furuya 2015	JGR
Vel	Data	Greenland & periphery IV from Sentinel-1	5	Nagler 2015	RS
Vel	Data and Change	Velocity of gl around Muztagh Ata (Pamir) from TSX	13	Holzer 2015	TC
Vel	Data and Change	Winter speed-up of glaciers in Yukon, Canada, from PALSAR	2	Abe & Furuya 2015	TC

Table 2.2: New literature relevant for Glaciers_cci. The 'et al.' has been left out in the Reference column, dDEM is DEM differencing. All publications are listed in the References.

When analysing the above studies in regard to their regional coverage, there are a few regions where product generation (by itself or for change assessment and trend analysis) might not be necessary. However, in most cases the studies only cover a small region (area) or specific years (velocity). Hence, for the intended large-scale data production of Phase 2 this is not an issue as the regions or dates already processed can be excluded or repeated for another period to extend temporal coverage of the FCDR. On the other hand, there are three important points justifying overlap in space and time: (1) cross-comparison with independently created results for accuracy assessment of the Glaciers_cci products, (2) the generated datasets are not made publicly available (e.g. contribution of outlines to GLIMS or the RGI) for whatever reason, and (3) the quality of the new datasets is too poor for (1) but they are made available nevertheless. In summary, data production will consider already published work for various purposes on a case-by-case basis. The above Table 2.2 has been used along with the user requirements summarized in the next section 2.3 to determine the key regions for data processing in year 2 and 3 (summarized in Table 2.4).

2.3 Review of user requirements and data access

Potential regions of interest by other user groups (e.g. IPCC and the RGI working group) are listed in the URD [RD1], while regions with data access restrictions can be found in the DARD [RD2]. From these documents we derive that a further quality improvement of glacier outlines in the RGI is required for several regions in High Mountain Asia (RGI regions 13, 14, 15) and the Southern Andes. These have thus to be part of the key regions to be selected. The 5th Assessment Report (AR5) of the IPCC further lists uncertainties resulting from a missing inventory of glaciers on the Antarctic Peninsula (API) as a major issue for improvement (URq_04). As the API is covered by the Antarctic_Icesheet_cci and several studies have recently been published (on outlines, DEM, and bed topography), work in this region needs to be coordinated among the involved CCIs (URq-14). Glaciers_cci will in any case look at the quality of outlines available for the sub-Antarctic islands and further improve these. For the other products (elevation change and velocity) the regional coverage is of limited importance and needs mainly to be coordinated with the above mentioned recently published work.

Access restrictions that have been identified in the DARD [RD2] mainly concern the limited availability of validation data. Hence, some of the Glaciers_cci products will be produced in regions where validation data are available (in general high quality datasets from independent assessments) for cross-comparison and accuracy assessment. Svalbard, Norway and the European Alps will be included for product validation and quality control to the extent possible.

2.4 Selected key regions for Phase 2

Based on previous works (see 2.1), the criteria described above (see 2.2), and user requirements (see 2.3), we have created a first matrix (RGI region vs products) of key regions to be investigated in Phase 2 (Table 2.3). Due to the on-going parallel activities of other research groups, this overview is subject to change and has to be revised each year. It is seen as a first overview and a starting point for data production only. Regions 1, 2, 8, 10, 12 and 16 have been largely excluded due to known on-going work by other researchers (e.g. through reviews and personal communication). The remaining regions are highlighted in grey. A third dimension has been added by indicating the type of activity foreseen in each region (e.g. data production, validation).

RGI Region	Area	Elevation Ch. Altimetry	Elevation Change DEM Differencing	Velocity
(01) Alaska	-	-	-	-
(02) Western Canada and USA	-	-	-	-
(03) Arctic Canada (North)	-	P, V	-	P
(04) Arctic Canada (South)	P/Q, C	P, V	-	P
(05) Greenland GICs	P, C, V	P, V	P	P*, C*
(06) Iceland	-	P	V	P,V
(07) Svalbard and Jan Mayen	-	P, V	P,V	P, C, V, X
(08) Scandinavia	-	P	P,V	P*
(09) Russian Arctic	P	P	-	P
(10) North Asia	-	-	-	-
(11) Central Europe	P/Q, C, V	-	V	-
(12) Caucasus and Middle East	-	-	P	P
(13) Central Asia	P/Q, C, V	-	P	P,C
(14) South Asia (West)	P/Q, C, V	-	-	C
(15) South Asia (East)	P/Q	P	P	P, C
(16) Low Latitudes	-	-	-	-
(17) Southern Andes	P/Q, C, V	-	P	P*
(18) New Zealand	-	-	P	P,C
(19) Antarctic and Subantarctic	P/Q, V	P, V	-	P

*Table 2.3: Key regions selected for each product in Glaciers_cci Phase 2. P denotes regions for product generation, V regions for potential validation, X regions for cross-comparison, and * where test sites will be tried. For the area product, C denotes regions for change detection and Q for quality improvement of the RGI. Regions and region numbers are as defined by the RGI (see Fig. 2.1).*

In Table 2.4 we provide an overview of already achieved (years 1 and 2) and further planned (year 3) work in regard to data production for the various sub-regions of the RGI. The general goal in year 2 is looking at glacier changes for all three products (abbreviated A, E and V in Table 2.4). This requires processing datasets from further epochs and subtracting results from each other to determine the change. Depending on data availability, the focus will be on an earliest (e.g. 1985-1990) and latest (e.g. 2010-2015) epoch using Landsat 5 and 8 (and maybe Sentinel 2) for area to supplement the existing year 2000 outlines. For the other products dates will be different but more recent outlines are required in several cases (e.g. as a mask for velocity fields from Sentinel 1 for Svalbard and Novaya Zemlya).

Work from year 2 will be continued in year 3 and some further regions and other dates will be added. For glacier area an update of exitsing glacier outlines is planed with Landsat 8 and Sentinel 2 for the Alps (S2), selected regions on Greenland (Disko Island and north of it), Svalbard (glaciers with strong changes), Novaya Zemlya, South Georgia and Patagonia (all with L8). Additionally we will look at the 1960s to 1980s using Corona and Hexagon data (for length/area changes and elevation changes). Elevation changes will also be derived in regions where we will get TanDEM-X data (currently only Svalbard), the Antarctic Peninsula and the glaciers on Greenland. Velocity fileds from Sentinel 1 (and also Sentinel 2 and Landsat 8) will be computed for most key regions and the 2013-2016 period, partly also going back tin time to now decommissioned sensors (e.g. PALSAR, ERS1/2). A final version of Table 2.4 will be provided in a final update of this document.

RGI Region	Region	Year 1	Year 2	Year 3
(03) Arctic Canada (North)	Ellesmere	A/E: none, V: Palsar	V: t+1 (S1)	A/E: none V: t0 (PALSAR), t+1 (S1)
(04) Arctic Canada (South)	Baffin	A/E/V: none	A: t±1 (Landsat), V: t0 (PALSAR)	A/V: t+1 V: t0 (PALSAR), t+1 (S1)
(05) Greenland GICs	subregions for A and V, E (CS2): all	A/E: none, V: TSX	A: t+1 (OLI) E: t+1 (CS2) V: subreg. (TSX, S1/2)	A: t+1 (OLI) E: t-1 (SPOT) V: t+1 (S1/2)
(06) Iceland	-	A/E/V: none	V: t+1 (TSX)	V: t+1 (TSX)
(07) Svalbard/Jan Mayen	Svalbard only	A: none, E: selected gl., V: selected gl. (Palsar)	A: t+1 (OLI), E: t+1 (CS2), V: t+1 (S1), t-1 (JERS-1)	A: t+1 (OLI) E: t+1 (TDX) V: t+1 (S1)
(08) Scandinavia	-	E: DEM tests	E: selected gl. (ASTER)	E: t+1 (ICESat)
(09) Russian Arctic	Novaya Z. FJ Land	A/E: none, V: Palsar	A: t+1 (OLI), V: t+1 (S1), V:t-1 (JERS-1)	A: t+1 (OLI) V: t+1 (S1)
(11) Central Europe	Alps	A t+1 (aerial, CH)	A: t±1 (Landsat, S2)	A: t+1 (S2)
(12) Caucasus/Middle East	-	A/E/V: none	V: t0 (Palsar)	V: Palsar)
(13) Central Asia	Pamir	A: t0, E: t+1, V: Palsar	V: t+1(S1)	V: t+1 (S1)
(14) South Asia (West)	Karakoram	A: t0, E: t0-t1, V: Palsar	A: t±1, V: t±1 (S1)	A/E: t-2 (Keyhole)
(15) South Asia (East)	Himalaya	A: none	E: selected gl. (ASTER)	A/E/V: none
(17) Southern Andes	Patagonia	A: t±1	E: t-1, V: t+1 (TSX)	A: t+1 (OLI) V: t0 (PALSAR)
(18) New Zealand	-	A/E/V: none	E: selected gl. (ASTER)	
(19) Antarctic/Subantarctic	S. Georgia Alexander Island APeninsula	A/E/V: none V: t0 Palsar	A: t0, V: t+1 (TSX) V: t+1 (S1) A: t0	A: t+1 (OLI) V: t-1 (ERS1/2), E: t+1 (CS2) E: t+1 (CS2)

Table 2.4: Overview of already achieved (Year 1 & 2) and planned (Year 3) data production for all products (A: area, E: Elevation change, V: velocity). FJL: Franz Josef Land. The abbreviation t±1 means an additional snapshot for the years around 1985 (t-1) and around 2015 (t+1) is foreseen (t0: year 2000). S1/2: Sentinel 1/2, CS2: Cryosat 2, TSX: TerraSAR-X.

3. Product specifications

The following sub-sections outline the specifications of the GO, SEC-altimetry, SEC-DEM differencing and IV products. In continuation from Phase 1, SEC measurements will be supplied in two separate products, altimetry and DEM differencing, as the individual strengths of the techniques are better suited to measuring differing, but complementary, glacier types. The two products have different specifications and so are treated separately here.

The product specifications are based on the user requirements and the attributes of the available data. They include the anticipated spatial and temporal coverage, frequency, resolution and accuracy. Please note that specifications of the products may ultimately differ as a result of data quality issues that cannot be known ahead of product generation. The product formats are addressed in Section 5.

3.1 Glacier Outlines

The glacier area product (GO) will be created with two key objectives in mind: (1) Further quality improvement of the RGI and (2) change assessment in key regions. Exact dates and scenes to be processed will be determined on a case-by-case basis. The general rule will be to use Landsat scenes (ETM+ sensor) around the year 2000 for objective (1) and have at least three points in time (around 1985, 2000, 2014) for (2) using data from the sensors TM, ETM+, and OLI. For objective (2) we will also consider Landsat MSS scenes back to 1972 and Corona/Hexagon scenes back to 1961 as available and appropriate in regard to snow and cloud conditions. Owing to the arbitrary imaging schedule, the latter are often poor for these sensors and we will focus on changes of the terminus position rather than mapping entire glaciers. This applies also to MSS data due to their poor spatial resolution. All details will be available as part of the new climate research data package (CRDP). The exact format and meta-information that will be provided with the outlines is currently not fixed as code is developed at NSIDC for an easy integration of different data formats in the GLIMS database (e.g. the RGI format). At a minimum for the Glaciers_cci product, all glacier outlines will be corrected for seasonal snow, debris, water and shadow and each dataset comes with meta-information about the used satellite scenes (path, row, date) and the processing applied. Steps like intersection with drainage divides and calculation of glacier specific topographic parameters might be performed according to a standardized set of DEMs and algorithms as part of the GLIMS integration.

Product	EO Input Data	Geographic Location	Spatial Resolution	Temporal Range	Temporal Frequency	Anticipated Accuracy
Area (change)	Landsat TM, ETM+, OLI	Key regions globally	30 m	1984-2014	3 time slices	better 5%
Area (change)	MSS / Corona	Key regions globally	60 / ~10 m	1972-1982 1961-1972	1 time slice each	better 10%
Area (RGI)	TM/ETM+	poor in RGI	30 m	~ 2000		better 5%

Table 3.1 Product specification for the glacier area product. Further details are listed in section 5.1.

3.2 Surface Elevation Change - Altimetry

Repeat altimetry will be used to provide measurements of surface elevation change over large ice caps and, on a regional scale, for highly glacierized regions (a key parameter identified by GCOS). Continuing from Phase 1, where a main focus was to establish a feasible and effective approach for generating elevation change datasets using repeat track altimetry, the key focus of Phase 2 will be to provide globally distributed times series of SEC measurements using that approach (RD3- TR-14 – see Appendix for full requirement). Phase 2 will also incorporate data from CryoSat-2 that was not available during Phase 1. Prioritisation of regions for product generation over the course of Phase 2 is based on the assessment of key regions as presented in Table 2.3 and Section 2 of this report. As outlined in the DARD [RD 2], due to the free availability and global coverage of the required EnviSat, ICESat and CryoSat-2 satellite altimetry data, we foresee no issues with restrictions for data access at the global scale. However, spatial coverage may be limited over ice caps and glaciers which are small relative to the satellite track spacing or with surface conditions not suitable for satellite altimetry (i.e. where slopes are too steep or the terrain too rugged). The measurements will be provided as a mean for the target area and so the resolution of the SEC measurements from altimetry will be at the basin scale or ice cap scale.

The temporal coverage of the SEC measurements from altimetry will span the operational periods of the EnviSat, ICESat and CryoSat-2 sensors, i.e. from 2002 onwards. The time series of data will therefore cover a minimum of 12 years (2002 to 2014) and in doing so will meet the requirement of GCOS for decadal resolution measurements (RD1- URq_02 – see Appendix for full requirement). For glaciers, only ICESat (2003-2009) is suitable. EnviSat, ICESat and CryoSat-2 were all nominally acquired with temporal repeats of less than 35 days (although, for ICESat, this was not regular due to the campaign style acquisitions) [RD2], therefore, where data volume allows, it should be possible to meet the User Requirement (RD1-URq_15 – see Appendix for full requirement) for seasonal and annual resolution SEC measurements from altimetry.

The typical accuracy of SEC measurements from satellite altimetry are < 0.5 m/yr (Moholdt et al. 2010, Flament and Remy 2012, McMillan et al. 2014) for large ice caps. The typical accuracy for small glaciers is similar, but can be variable depending on the coverage of glaciers and altimetry data (Nuth et al. 2010, Nuth and Kääb 2011, Kääb et al. 2012, Kääb 2008). We expect our measurements to have similar accuracy to those reported in the literature and therefore will meet the accuracy required by GCOS (RD1-URq_02 – see Appendix for full requirement). The specification of the SEC altimetry product may be summarised as follows:

Product	EO Input Data	Geographic Location	Spatial Resolution	Temporal Range	Temporal Frequency	Anticipated Accuracy
SEC-Alt (Ice Caps)	EnviSat, ICESat & CryoSat-2	All large ice caps globally	Mean basin scale elevation change	2002 onwards	Seasonal and Annual	< 0.5 m/yr
SEC-Alt (small glaciers)	ICESat	All major glaciated regions globally	Mean basin scale elevation change	2003-2009	Seasonal and Annual	< 0.5 m/yr

Table 3.2: SEC Altimetry product specification.

3.3 Surface Elevation Change – DEM differencing

DEM differencing is used to provide measurements of surface elevation change over glaciers and ice caps (a key parameter identified by GCOS). Continuing from Phase 1, where a key focus was to establish a feasible and effective approach for generating elevation change datasets using DEM differencing, the key focus of Phase 2 will be to provide globally distributed sets, and time series where possible, of SEC measurements using that approach (RD3- TR-14 – see Appendix for full requirement). Prioritisation of regions for product generation over the course of Phase 2 will be based on the User Requirements and the assessment of key regions as presented in Section 2. Over the 3-year period of the project we will produce measurements over the Arctic and Antarctic (outside the ice sheet) and over mid-latitudes.

As outlined in the DARD [RD2], due to the free availability of the required data (with the exception of TanDEM-X data for which we are awaiting licensing), we foresee no issues with restrictions for data access. However, product generation may be limited by the availability of suitable scenes. It should also be noted that data voids may occur within any of the DEMs, potentially limiting the spatial coverage of elevation change obtained from a given DEM pair. Reasons for these voids can be manifold, depending on the methods used for DEM generation (e.g. failed correlation for optical stereo, lack of phase coherence for InSAR, perspective obstruction by adjacent terrain, etc.). At all locations where at least one DEM has a void also the differential DEM (dDEM) will have a void (i.e. a no-data value). Several methods exist to bridge these dDEM voids in order to arrive at glacier volume changes. Void filling is different from case to case because the DEMs used and the void locations are different so that their effect on the dDEM will be different. The applied DEM pre-processing or dDEM post-processing will be reported in the meta-information file. The spatial resolution of SEC-dDEM depends upon data availability but is about 100 m globally, with higher resolutions (30-50 m) available for local glaciers and smaller regions.

The temporal coverage of the SEC measurements from DEM differencing will span the operational periods of ASTER, SRTM, SPOT5 HRS SPIRIT missions, i.e. 2000 onwards; and where available national DEMs, i.e. 1960 onwards. The time series of data will therefore cover a minimum of 14 years (2000 to 2014) and in doing so will meet the requirement of GCOS for decadal resolution measurements (RD1-URq_02 – see Appendix for full requirement). DEM differences cannot be provided as seasonal or annual products as (i) suitable DEMs are typically only available at decadal time scales, and as (ii) the typical vertical accuracy of such DEMs is too low to estimate SEC at seasonal and annual time scales at a statistically significant level.

We expect DEM differences for ASTER-derived DEMs or the SRTM DEM to be accurate to within 5-10 m depending heavily on local conditions. The GCOS target requirement for horizontal resolution of 30-100 m is expected to be met in most cases. The accuracy of the TanDEM-X DEM (i.e. the promised WorldDEM) over glaciers will be tested within Glaciers_cci once datasets are made available. The specification of the SEC DEM differencing product may be summarised as follows:

Product	EO Input Data	Geographic Location	Spatial Resolution	Temporal Range	Temporal Frequency	Anticipated Accuracy
dDEM	ASTER, SPOT5 HRS (SPIRIT), SRTM, TanDEM-X, DEMs from national mapping agencies	Most glaciers and ice caps globally once	100 m (regionally higher)	first DEMs from mapping agencies 1950s to present	few years for large changes, otherwise about a decade; at least one period, if possible several	better 10% for large chan-ges, better than 0.5 m / year for small changes

Table 3.3: SEC DEM Differencing product specification.

3.4 Ice Velocity

Optical image matching and SAR offset-tracking will be used to determine surface velocity fields over glaciers and ice caps (a key parameter identified by GCOS). Continuing from Phase 1, where a key focus was to establish feasible and effective approaches for generating surface velocity fields with these methods, the key focus of Phase 2 will be to provide one global set of velocities, and globally distributed times series of ice velocity (IV) measurements for selected regions (RD3- TR-15 – see Appendix for full requirement). Newly available data sets that will be incorporated in Phase 2 include Landsat-8 for optical tracking, and Sentinel-1 and possibly ALOS-2 for SAR. Prioritisation of regions for product generation over the course of Phase 2 will be based on the User Requirements and the assessment of key regions as presented in Section 2. Over the 3-year period of the project we will produce measurements over the Arctic, the Sub-Antarctic islands and over the mid-latitudes. As outlined in the DARD [RD2], for optical tracking, due to the free availability and global coverage of the required ASTER and Landsat series to consortium members, we foresee no issues with restrictions for data access at the global scale. A main limitation is cloud cover, which does not allow the production of IV products in certain glacier regions. Spatial coverage is affected by the considerable data voids over a number of regions for the older satellites. On the other hand, suitable SAR data are not globally available and production will be affected from both the existence of a suitable archive of data and the conditions to access these images for non-ESA missions (e.g. ALOS PALSAR, Radarsat-2 and TerraSAR-X, TanDEM-X).

The successful estimation of glacier motion from space depends on the conservation of intensity or phase variations over time. With optical data the glacier has to show pronounced features of visual contrast such as crevasses and debris features that are stable over time. The successful estimation of the local image offsets from SAR data depends on the presence of nearly identical features in the two images at the scale of the employed patches. These issues translate to differences in the product characteristics in regard to the temporal resolution and regions on the glacier where this information can be derived. For example, optical image matching does usually not work over snow or firn-covered accumulation areas, and SAR offset-tracking is difficult to apply on small glaciers. In both cases, an accurate DEM is required for product generation. The 5% accuracy requirement according to IGOS (2007) translates to a ±15 m / year accuracy for a 300 m / year displacement. This can be provided by image matching techniques where sufficient image contrast is present, but likely not over the entire glacier surface. Ultimately a combination of SAR and optical data will give the most complete global and temporal coverage and we therefore consider homogenisation and synergistic use of SAR and optical data in order to generate time series of velocity maps, independent of the sensor.

For optical tracking, satellite images need to be of medium, high or very high resolution, i.e. better or equal to 30 m for large glaciers, better or equal to 15 m for medium-size glaciers, even better for smaller glaciers.

The temporal coverage of the IV measurements from optical tracking will span the operational periods of the Landsat TM and ASTER sensors, i.e. 1984 onwards. The time series of data will therefore cover up to 30 years (1984 to 2014), less though for regions with insufficient coverage (at least though approx. 2000-2014). In doing so, we will meet the requirement of GCOS of monthly to annual resolution (RD1-URq_03 – see Appendix for full requirement).

For SAR tracking, satellite images need to be of high to very-high resolution, i.e. better or equal to 20 m for large glaciers, better or equal to 3 m for medium-size glaciers. The temporal coverage of the IV measurements from SAR tracking of high-resolution sensors will span the operational periods of the ERS-1/2, JERS-1, ENVISAT, Radarsat-1 and ALOS PALSAR sensors, i.e. 1991 onwards. Very-high resolution data acquired by Radarsat-2, TerraSAR-X, TanDEM-X or Cosmo-Skymed are typically available on-demand for a restricted number of glaciers since 2007.

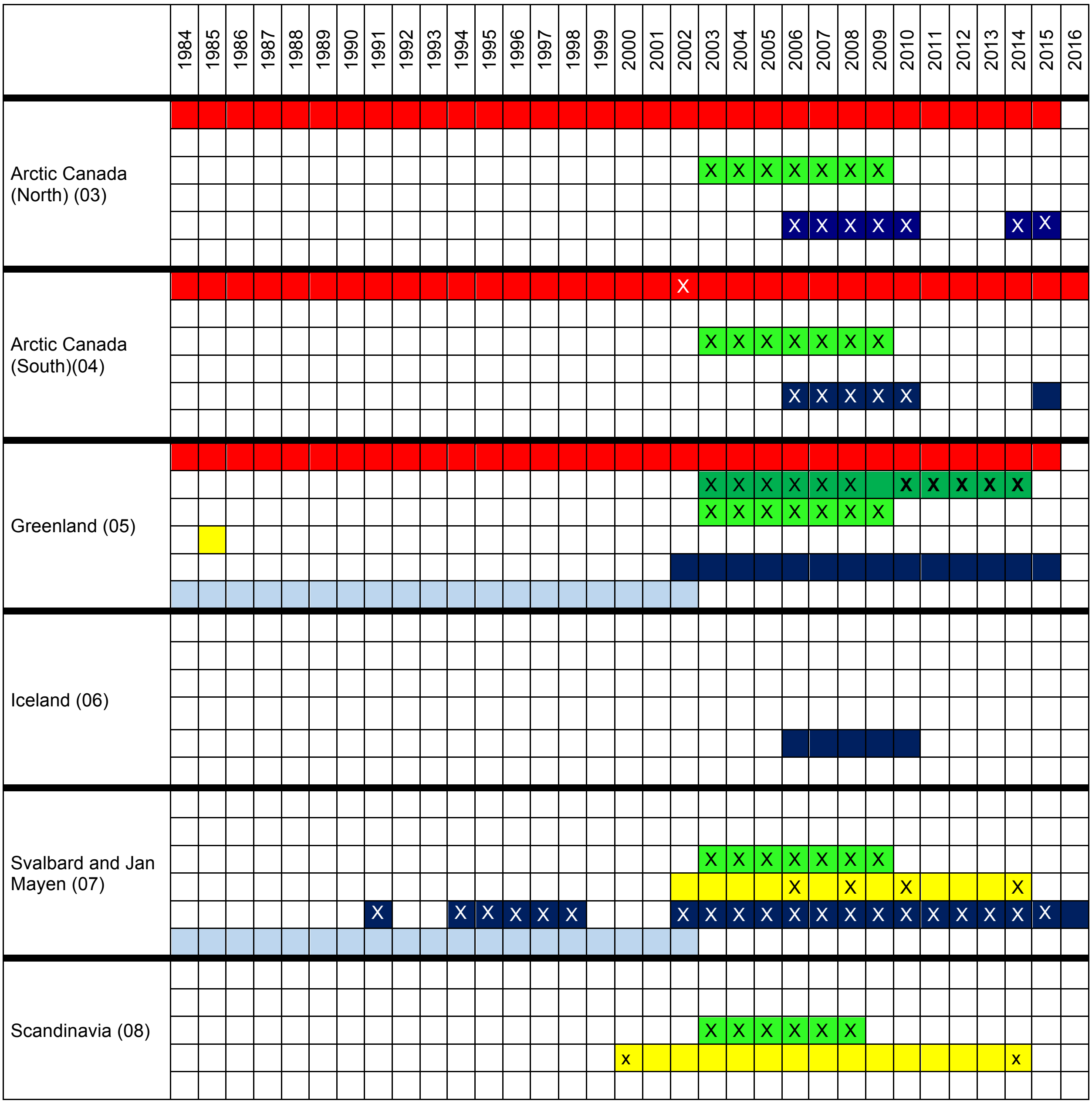
For velocity, EO products aim to achieve <100 m horizontal resolution, monthly to annual resolution, and better than 5% accuracy and therefore will meet the accuracy required by GCOS (RD1-URq_03 – see Appendix for full requirement). The specification of the velocity product may be summarised:

Product	EO Input Data	Geographic Location	Spatial Resolution of Product	Temporal Range	Temporal Frequency	Anticipated Accuracy
Velocity Map Standard	high-resolution SAR and optical (1)	regional to global (3, 4)	100-200 m	1984 to present (4)	5 years to decadal (4)	< 15 m/y
Velocity Map Advanced	very high-resolution SAR and optical (2)	local, selected glaciers (3, 4)	< 50 m	1999-present (4)	Annual (4)	< 5 m/y (TBC)

Table 3.4: Velocity product specifications and spatial and temporal coverage. Numbers in superscript denote: (1) Optical: Landsat, ASTER, SPOT, ALOS AVNIR, ALOS PRISM; SAR: ERS-1/2, JERS-1, ENVISAT, Radarsat-1, ALOS PALSAR, Sentinel-1; (2) Optical: Ikonos, Geoeye, Pleiades, WorldView, etc.; SAR: Cosmo-SkyMed, TerraSAR-X and Radarsat-2; (3) Optical: excluding snow-covered or firn-covered accumulation areas; SAR: excluding relatively small glaciers and areas of fast glacier flow and wet snow; (4) Depending on data availability and access.

4. Product coverage synthesis

A synthesis of the anticipated spatial and temporal coverage of the different techniques, highlighting the complementarities of the different products, is given in Figure 4.1. The periods indicated for the glacier area product refer to the period that will be analysed in each region for finding appropriate scenes. In general, regions where change assessment will be performed will focus on glacier extents from three points in time (around 1985, 2000 and 2014) while those created for quality improvement of the RGI will only refer to one point in time (around 2000). It should be noted that the final product coverage may differ slightly as a result of unforeseeable data/processing issues. We denote the areas where data production has taken place for a given technique with 'x's in Table 4.1.



	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Russian Arctic (09)																														X	X		X
																				X	X	X	X	X	X	X							
Central Europe (11)																																X	
Caucasus and Middle East (12)																																	
Central Asia (13)																																	
																							X	X	X	X	X					X	X
South Asia (West) (14)															X	X	X	X	X	X							X						
																							X	X	X	X	X					X	X
South Asia (East) (15)																																	
																				X	X	X	X	X	X	X							
																			X	X	X	X	X	X	X	X	X	X	X				
Southern Andes (17)		X															X										X						X
New Zealand (18)																																	
																	X	X	X	X	X	X	X	X	X	X	X	X					

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Antarctic and Subantarctic (19)																	X	X	X	X												X	
																							X	X	X	X	X	X		X		X	

Table 4.1: Spatial and temporal coverage of the GO (red), SEC-alt-alt (green), SEC-alt-dem (light green), SEC DEM differencing (yellow), and IV optical and SAR (dark blue) and optical 1984-2000 depending on archives (light blue) products. Regions and region numbers are as defined by the RGI (Pfeffer et al., 2014). Crosses denote regions where data production has taken place.

5. Product formats

This section describes the product formats for GO, SEC–Altimetry, SEC–DEM Differencing and IV. For consistency, the product formats will largely follow those used in Phase 1, where there will be modifications for Phase 2, these are described in the Sections 5.1 and 5.2. Due to the different nature of the products their formats differ and so the different products are treated separately. Table 5.1 provides a summary of the product formats.

Product	File type	Coordinate type	Metadata format	Filename format
GO (CRDP) GO(RGI)	Shapefile Shapefile	UTM (WGS84) Geographic (WGS84)	as in Phase 1 (See Table 2.2 in Phase 1 PUG) – with some changes as outlined below	as in Phase 1 in progress
SEC - Alt	ASCII	Geographic/UTM (WGS84)	As Phase 1 – see CRDP for eg.	As Phase 1 - see CRDP for eg.
SEC - DD	Geotiff	Geographic/UTM (WGS84)	As Phase 1 – see section 4.3.1 of Phase 1 PSD	As Phase 1 – see section 4.3.1 of Phase 1 PSD
IV	ASCII	Geographic/UTM (WGS84)	See Section 5.2 below	As Phase 1 – see section 5.3.2 of Phase 1 PSD

Table 5.1: Product formats for Glaciers_cci Phase 2

5.1 Metadata format for glacier outlines

The metadata format for the glacier area product has changed during Phase 1. Originally it was planned to provide all data in the GLIMS format (see Phase 1 PSD). With the compilation of the RGI it was possible to only submit corrected outlines, basically without any further meta-information (apart from date, path and row of the satellite scene used). The metadata required for the RGI (see Table 2.2 in the PUG of Phase 1) was centrally added and included the intersection of glacier complexes with drainage divides from a standardized algorithm. Automated data assimilation and attribute assignment is currently being developed at NSIDC for the integration of RGI outlines in the GLIMS database. The result of this centralized processing will be reported in the next update of this document.

5.2 Metadata format for elevation changes

A detailed description of the metadata provided with the elvation change products is given in sections 4.3.1 (dDEM) and 4.3.3 (altimetry) of the Phase 1 PSD (Glaciers_cci, 2011).

5.3 Metadata format for ice velocity

The metadata for SAR is given below just as an example, it will look very similar for optical sensors apart from the specific entries. The possibility to merge velocity from optical with microwave sensors is further explored. In particular the higher spatial and / or radiometric resolution of Landsat 8 pan and Sentinel 2 might allow for monthly means also from optical data. So for the applications foreseen in Option 1 we will likely go the other way round (i.e. creating a multi-year mean with better coverage).

The metadata file for the velocity product (example for SAR) will contain the following keys:

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	<Version>V01</Version>
	<Dated>2010608</Dated>
</MetadataFile>

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	<quicklookFilename>xxxxxxxxxxxxxxx.jpg </quicklookFilename >
</link>

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	<software>IRSL</software>
	<softwareVersion>2.1</softwareVersion>
	<processinDate>20101209T221014</processingDate>
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        &lt;Affiliation&gt;ENVEO&lt;/Affiliation&gt;
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Abbreviations

ALOS	Advanced Land Observation Satellite
API	Antarctic Peninsula
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATM	Airborne Topographic Mapper
AVNIR	Advanced Visible and Near Infrared Radiometer
DARD	Data Access Requirements Document
dDEM	DEM differencing
DEM	Digital Elevation Model
dm/dt	Mass change
EO	Earth Observation
ERL	Environmental Research Letters
ERS	European Remote Sensing
ETM	Enhance Thematic Mapper
GCOS	Global Climate Observation System
GLIMS	Global Land Ice Monitoring from Space
GO	Glacier Outlines
GPC	Gound Control Point
GRL	Geophysical Research Letters
ICESat	Ice, Cloud and Elevation Satellite
IGOS	Integrated Global Observing Strategy
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel for Climate Change
IV	Ice Velocity
JERS	Japanese Earth Resources Satellite
MSS	Multi Spectral Scanner
NSIDC	National Snow and Ice Data Center
OLI	Operation Land Imager
PALSAR	Phased Array type L-band Synthetic Aperture Radar.
PRISM	Polar Radar for Ice Sheet Measurements
PSD	Product Specification Document
PUG	Product User Guide
RGI	Randolph Glacier Inventory
SEC	Surface Elevation Change
SPI	Southern Patagonia Ice Field
SPIRIT	Stereoscopic survey of Polar Ice: Reference Images and Topography
SPOT5 HR	Satellite Pour l'Observation de la Terre 5 High Resolution
SRTM	Shuttle Radar Topography Mission
TM	Thematic Mapper
TS-X	TerraSAR-X
URD	User Requirements Document
URq	User Requirement
UTM	Universal Transverse Mercator
VAL	Validation
WGS	World Geodetic System

Appendix

Technical requirements from RD3 as referenced in the text:

[TR-14]	Glacier_cci **shall** for Elevation Change: In year 1: Determine glacier and ice cap elevation changes within the specifiedkey regions specified by the user community in the updated URD for altimetrysensors (see [TR-20]) and DEMs globally. Modify the system to accommodateterrain corrections based on altimetry data and develop a processing chain forCryoSat-2 data. In year 2: Continue the work from year 1 to extend the assessments from altimetry and DEM differencing to all glacierized regions and incorporate results into GLIMS/WGMS databases as appropriate. In year 3: Apply the DEM-differencing method to upcoming new DEMS (e.g.TanDEM-X). Develop elevation changes from CryoSat 2 altimetry within theglacier outlines falling in the CryoSat 2 region of coverage.
[TR-15]	Glacier_cci **shall** for Ice Velocity: In year 1: Extend optical and SAR processing to all glacierized regions so as provide cover for as much of RGI as possible. In year 2: Continue the work from year 1 and conduct temporal trend analysis for key regions. In year 3: Continue the work from year 2 and apply the method to Sentinel-1 SAR and Sentinel-2 MSI.

User requirements from RD1 as referenced in the text:

URq_02	For SEC, EO products aim to achieve 30-100 m horizontal resolution (*DEM differencing only), 1 m vertical resolution, decadal temporal resolution, better than 5 m accuracy [* better than 5-10 m for DEM differencing], and 1 m stability
URq_03	For IV, EO products aim to achieve point to 200 m horizontal resolution, monthly to annual resolution, and better than 5% accuracy.
URq_15	Produce seasonal and annual SEC product [*** altimetry only]