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User Requirements Document (URD)

glaciers cci

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Document status sheet

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Document purpose and scope

This User Requirements Document (URD) assesses requirements relevant to the Glaciers_cci+ Phase 2 project from the international glaciological and climate research communities. It collects those requirements from relevant publications and inter-group communication, and discusses their feasibility. Among others, the results will be used to guide the project specifications.

In this document, specific user requirements are assigned a requirement ID reference code named 'URq_XX'. As a starting point, IDs 1 to 19 have been copied across from the Glaciers_cci project, and updated where necessary. This will facilitate cross-referencing and traceability between multiple CCI and CCI+ documents. For the final CCI equivalent to this document, see [2].

1. Introduction

1.1 ESA Glaciers CCI+ and its requirements

The European Space Agency (ESA) established the Climate Change Initiative (CCI) suite of projects in 2009 to utilise its long-term global Earth observation archives to inform worldwide policy decision on climate change mitigation and adaptation. The Global Climate Observing System (GCOS) has defined a range of essential climate variables (ECVs) that critically contribute to the characterisation of the climate.

Glaciers_cci, which ran from 2011 to 2017, contributed to efforts towards a globally complete and detailed glacier inventory. It contributed glacier outlines in key and previously unmapped regions to the Randolph Glacier Inventory (RGI), the Global Land Ice Measurements from Space (GLIMS) database, and co-operated in efforts to enhance the integrity and error characterisation of available datasets.

The first phase of Glaciers_cci+ built on the experience of the Glaciers_cci project, to investigate the history and current state of dynamically unstable glaciers in two key regions:

- High Mountain Asia (e.g. Karakorum, Pamir, Kunlun Shan)
- Eastern Arctic (e.g. Svalbard, Franz-Josef-Land, Novaya Zemlya, Severnaya Zemlya)

based on three key parameters:
- Glacier outline (GO)
- Surface elevation change (SEC)
- Ice velocity (IV).

The project lasted for three years, starting in 2019, and communicated with the user community via publications, web resources, meetings and conferences. An expert group, the Climate Research Group (CRG), was set up to advise and provide feedback on the CCI projects.

Following on, the second phase of Glaciers_cci+ started in 2022, and will run until 2024. This phase's scientific aims are to:

- Characterise differences in glacier surges, on a global scale
- Investigate the initiation of surges
- Compare snow cover and length changes in surging and non-surging glaciers in High Mountain Asia

For Phase 2 an extra key region has been added, the Greenland Peripheral Ice Caps and Glaciers, to be assessed using radar altimetry.

As a first step, an overview was compiled of the existing body of relevant literature and the key science questions resulting from it. Research requirements were gathered from the latest Intergovernmental Panel on Climate Change (IPCC) assessment reports and its recent Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), as well as from related international organisations such as the Global Climate Observing System (GCOS). These requirements will be guiding principles during project planning, and cover every aspect of the work from technical demands such as data resolution to operational demands such as data dissemination pathways.

The Phase 1 Statement of Work [1] states:
"Detailed records of mass balance from in situ observations are available for relatively few glaciers and extend back on average 50 years. The target for the Glaciers ECV is therefore to populate, update and extend the existing records for primarily scientific users and key science bodies."
Once data are uploaded to the system (e.g. the GLIMS and WGMS database) they can be widely disseminated through the networks of the various cryospheric science organisations.

The user requirements are regularly reviewed throughout the project and were updated annually. If other important needs or regions of interest emerge they will be investigated on a case-by-case basis and this document updated as necessary.

This version 1.1 of the document is based on the last requirements document from Phase 1 of the project. Since that document was written, the main advance in user requirements has come from the recently published 2022 GCOS Implementation Plan [15], to which several Glaciers_cci+ consortium members contributed. This plan follows on from the 2016 publication [4], which was used during CCI+ Phase 1. The new plan adds extra details to each requirement, giving three sets of targets, at different levels of rigour. These are labelled G, B and T.

- G - goal, the ideal requirement
- B - breakthrough, a requirement leading to significant improvement in current datasets
- T - threshold, the minimum requirement for useful data.

One further source of recommendations, specific to High Mountain Asia (HMA), is the International Centre for Integrated Mountain Development (ICIMOD) book "The Hindu Kush Himalaya Assessment (Wester et al, 2019)". This comprehensive review on the effects of climate change on the Himalayan region contains a chapter on the current status of, and changes occurring in, the cryosphere.

1.2 User requirements document structure

This document is structured as follows:

- Chapter 2 outlines the users of the glacier products and potential synergy with related initiatives,
- Chapter 3 describes the requirements from user community organisations,
- Chapter 4 assesses the scientific feasibility of meeting the identified user requirements,
- Chapter 5 provides a summary table of the requirements and uncertainty targets to be developed within the project.

2. Users of glacier data and related initiatives

Glaciers react to climatic forcing on timescales typically from years to decades, and satellite monitoring of glaciers has sufficient history to allow analysis of past and present records. Changes in glaciers provide natural evidence of climate change. Changes in glacier area and surface elevation can be converted into contributions to global mass balance and runoff, while velocity helps estimate mass flux. All these parameters feed into the global sea-level budget.

Glaciers_cci+ will contribute data to the scientific community, which will be of interest to users working in fields such as climate monitoring and modelling. In a wider context, it will also overlap with science projects using similar techniques and producing similar datasets, e.g. those working on related ECVs. Cross-project collaboration and co-ordination are on-going.

2.1 Users of glacier data

The main users of the data fall into several categories, described in Table 1 below.

Table 1: Types of data users.

User interest	Example usage
Glacier modellers	Validation, constraint and initialisation of models
Earth observation scientists	Deriving volume and mass change, and mass budgets
Mass balance measurements	Glacier extents, geodetic mass balance for calibration
Surface mass balance modellers	Interpretation of observed mass changes
Climate modellers	Incorporating glacier/climate interactions within Earth system models
Policy makers – political and practical	Monitoring changes for water availability, hydro-power, etc.
General public and media	Visualisations and information relating to climate change impacts

2.2 Related initiatives and cross-CCI activities

Glaciers_cci collaborated with three other CCI projects, Landcover, Antarctic Ice Sheet and Greenland Ice Sheet, all of which have been extended to CCI+. Glaciers_cci+ continues to work with them, as well as two new CCI+ projects, Snow and Permafrost. The Climate Modelling User Group (CMUG) is a pan-CCI project. Close cooperation of ESA with the Copernicus Climate Change Service (C3S) of the European Union is on-going. C3S is an ECV data provision service that takes up R&D results of CCI in its glacier service.

At global level, a co-ordinated glacier monitoring system has been set up, the Global Terrestrial Network for Glaciers (GTN-G) that is operated by WGMS as part of GCOS and its Terrestrial Observation Panel for Climate (TOPC). Additionally, the Integrated Global Observing Strategy (IGOS), now replaced by Global Cryosphere Watch (GCW), was concerned with strategic planning of requirements for satellite observations and was set up by several partners including the Committee on Earth Observation Satellites (CEOS) and the Global Terrestrial Observing System (GTOS, now no longer operating).

The US based National Snow and Ice Data Center (NSIDC) administers the Global Land Ice Measurements from Space (GLIMS) database, which also hosts the Randolph Glacier Inventory (RGI). Independently working in the same scientific area are the Ice sheet Mass Balance and Intercomparison Exercise (IMBIE), and the International Association of Cryospheric Sciences (IACS) working groups on the RGI and the Regional Assessments of Glacier Mass Change (RAGMAC). An overview of the related initiatives is given in Table 2 below.

Table 2: Overview of projects and initiatives related to Glaciers_cci.

Project	Web address	Description	Synergy
Antarctic Ice Sheet CCI+	http://esa-icesheets-antarctica-cci.org	An ESA CCI project to produce data records of mass balance, ice velocity, surface elevation change and grounding lines in Antarctica	Common consortium members allow communal development of algorithms for elevation change and velocity products
Greenland Ice Sheet CCI+	http://esa-icesheets-greenland-cci.org	An ESA CCI project to produce data records of surface elevation change, ice velocity, calving front location, grounding line location and gravimetric mass balance in Greenland	Common consortium members allow communal development of algorithms for surface elevation change and velocity products
Landcover CCI+	http://esa-landcover-cci.org	An ESA CCI project to generate global land cover products	Global glacier outlines are considered as a land cover type
Permafrost CCI+	http://cci.esa.int/Permafrost	An ESA CCI project to develop and deliver permafrost maps as ECV products	Glacier outlines are incorporated into permafrost modelling
Snow CCI+	http://cci.esa.int/node/274	An ESA CCI project to produce global maps of snow cover area extent and snow water equivalent	Snow products can be used to constrain glacier outlines
Sea-level budget closure	https://climate.esa.int/en/projects/sea-level-budget-closure/	An ESA CCI Cross-ECV project to test if the sea level budget can be closed with currently available datasets	Global glacier outlines as a main input for modelling
CMUG	https://climate.esa.int/en/projects/cmug/	A dedicated forum through which the earth observation and climate modelling and reanalysis communities can work together	Development of product formats
C3S	https://climate.copernicus.eu	A data service providing information about past, present and future climate in Europe and globally	Data dissemination
GCW (formerly IGOS / GTOS)	https://globalcryospherewatch.org/	A program for observations, modelling and analysis of terrestrial ecosystems to support sustainable development	Incorporation of datasets into global observing strategy
GCOS	https://gcos.wmo.int	A coordinating body of the WMO in support of the United Nations Framework Convention on Climate Change	Status assessment of global climate observations
WGMS	https://wgms.ch	A service that compiles and disseminates standardised data on glacier fluctuations	Surface elevation change products incorporated into WGMS data pool
NSIDC	https://nsidc.org	An organisation managing and distributing cryospheric data (incl. tools for data access), providing user support, performing scientific research and educating the public about the cryosphere	Dissemination of GLIMS data, the WGI and RGI
GLIMS	https://glims.org	A project to monitor the world's glaciers, primarily using data from optical satellite instruments	Glacier outlines and velocity products incorporated into GLIMS database, provision of guidance on data standards
IACS RGI working group	https://cryosphericsciences.org/rgi-working-group	A group maintaining and further updating the RGI glacier inventory dataset	Glacier outlines incorporated into RGI data pool
IACS RAGMAC working group	https://cryosphericsciences.org/activities/wg-ragmac/	A group established to produce regional and global evaluations of glacier mass changes	Prepare a new consensus estimate of global glacier mass changes with uncertainties
IMBIE	http://imbie.org	An international collaboration providing improved estimates of the ice sheet contribution to sea level rise	Common consortium members allow communal development of satellite radar altimetry methods and algorithms
GLAMBIE	https://glambie.org	An international collaboration providing improved estimates of the glacier contribution to sea level rise	Standardised assessment of glacier elevation changes and its uncertainty

3. User requirements

Glaciers_cci assembled a list of 19 requirements, based on publications and recommendations from community groups and interested parties [2]. Those requirements are taken as a starting point, and for continuity they retain their CCI identification numbers, URq_01 to URq_19. Updates and new requirements have been considered and added as necessary. However, since Glaciers_cci+ is concentrated on two key regions, rather than globally, some of the CCI requirements no longer apply to CCI+ or are now taken over by C3S. Table 7 in Section 5 gives a complete listing of the requirements.

3.1 Requirements from community groups

Scientific communities with a special interest in products from the Glaciers_CCI+ project are listed below, with the IDs relevant to each of their requirements.

3.1.1 GCOS

GCOS regularly assesses the state of global climate observations and maintains definitions of ECVs. The ECV definitions used by Glaciers_cci+ Phase 1 were issued in 2019, with two ECVs (area and elevation change) relevant to glaciers [3]. The ice velocity ECV was defined for ice sheets, with no interpretation specific to glaciers. The latest update was issued in 2022 [16], again, with area and elevation/mass change products given specifically for glaciers, and ice velocity for ice sheets. It is a cardinal requirement (CR-1) of the CCI+ projects that they develop and validate algorithms to approach the GCOS ECV requirements [1]. Feedback will be provided from Glaciers_cci+ to GCOS via their Terrestrial Observation Panel for Climate (TOPC).

Relevant requirements: URq_01, URq_02

The full requirements are given below in Tables 3 to 6. Table 5 for ice velocity and Table 6 for snow cover, are only provided for comparison, as both are not specific to glaciers.

Table 3: GCOS requirements for glacier area. Codes are: G = goal, the ideal requirement, B = breakthrough, a requirement leading to significant improvement in current datasets, T = threshold, the minimum requirement for useful data.

Name	Glacier Area				
Definition	Inventory of map-projected area covered by glaciers.				
Unit	km^2				
Note	Glacier area is the map-projected size of a glacier in km^2. The product comes as worldwide inventory of glaciers outlines with various related attribute fields (e.g. area, elevation range, glacier characteristics). Typically, a minimum size of 0.01 or 0.02 km^2 is applied, to avoid including small ice patches which do not flow and are therefore not glaciers.				
Requirements					
Item needed	**Unit**	**Metric**	**[1]**	**Value**	**Notes**
Horizontal Resolution	m		G	1	Spatial resolutions better than 15 m (e.g. the 10 m from Sentinel 2) are preferable as typical characteristics of glacier flow (e.g. crevasses) only become visible at this resolution (Paul et al. 2016).
			B	20	The horizontal resolution of 15-30 m refers to typically used satellite sensors (Landsat and ASTER) to map glaciers.
			T	100	At coarser resolution the quality of the derived outlines rapidly degrades.
Vertical Resolution			G	-	N/A
			B	-	
			T	-	
Temporal Resolution	y		G	1	The temporal sampling "Annual" means that each year the availability of satellite (or aerial) images should be checked to identify the image with the best snow conditions (i.e. snow should not hide the glacier perimeter).
			B		
			T	10	Decadal data used to evaluate glacier change in regional scale.
Timeliness	y		G	1	
			B		
			T	10	For multi-temporal inventories at decadal resolution, the timeliness of the product availability is not so important.
Required Measurement Uncertainty	%	Random error of glacier outlines produced in dependency of remote sensing imagery used, with respect to the total glacier area	G	1	Glacier outlines mapped with a resolution of 1 m remote sensing images (take glacier area in average as 1 km^2)
			B	5	Glacier outlines mapped with a resolution of 15-30 m remote sensing images (take glacier area in average as 1 km^2)
			T	20	Glacier outlines mapped with a resolution of 100 m remote sensing images (take glacier area in average as 1 km^2)
Stability			G		Glacier area at different times extracted independently. No cumulative effect of the measurement system should be considered
			B		
			T		
Standards and References	Pfeffer, W. T. et al. The Randolph Glacier Inventory: a globally complete inventory of glaciers. J. Glaciol. 60, 537–552 (2014). Paul, F., S.H. Winsvold, A. Kääb, T. Nagler and G. Schwaizer (2016): Glacier Remote Sensing Using Sentinel-2. Part II: Mapping Glacier Extents and Surface Facies, and Comparison to Landsat 8. Remote Sensing, 8(7), 575; doi:10.3390/rs8070575. Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., … Vincent, C. (2015). Historically unprecedented global glacier decline in the early 21st century. Journal of Glaciology, 61(228), 745–762. http://doi.org/10.3189/2015JoG15J017				

Table 4: GCOS requirements for glacier elevation change. Codes are: G = goal, the ideal requirement, B = breakthrough, a requirement leading to significant improvement in current datasets, T = threshold, the minimum requirement for useful data.

Name	Glacier Elevation Change				
Definition	Glacier surface elevation changes from geodetic methods.				
Unit	m y^{-1}				
Note	Measured in-situ and remotely sensed using geodetic method (Cogley et al. 2011, Zemp et al. 2013)				
Requirements					
Item needed	Unit	Metric	[1]	Value	Notes
Horizontal Resolution	m		G	1	The fine resolution (1-5 m) data be used to extract mass change and dynamic characteristics in area with abnormal topography (quite steep slope, ice fall, calving snout)
			B	25	A stable size of raster for measuring volume change (Joerg and Zemp, 2014)
			T	90	Resolution of SRTM, which most widely used as reference to extract elevation change
Vertical Resolution	m		G	0.01	Annual mass change of glaciers be evaluated with data with vertical resolution < 0.01 m (e.g. Xu et al., 2019)
			B	2	Roughly corresponding to the resolution needed for annual mean mass change if observed decadal
			T	5	The targets for vertical resolutions refer to requirements for differences of digital elevation models (dDEM) in mountainous terrain (e.g. Joerg and Zemp, 2014)
Temporal Resolution	y		G	1	To evaluate annual mass change and detect the signal of potential abnormal events (e.g. surge)
			B		
			T	10	The frequency "decadal" refers to the length of the time period needed between two geodetic surveys in order to safely apply a density conversion from volume to mass change (cf. Huss 2013, Zemp et al. 2013)
Timeliness			G		In view of the low need for temporal sampling, the timeliness is not so important.
			B		
			T		
Required Measurement Uncertainty	m	Glacier-wide (random) uncertainty estimate based on a quality assessment of the digital elevation model differencing product over stable terrain	G		
			B	2	Refers to the glacier-wide uncertainty estimate based on a quality assessment of the dDEM product over stable terrain. The value of (2m per decade = 0.2 m^{-2} a^{-1}) is set in relation to the corresponding uncertainty requirement of the glaciological method.
			T		
Stability	m / decade	Glacier-wide bias in elevation change measurements over a decade	G		
			B	2	The stability of 2m per decade refers to a bias in the glacier-wide change of 0.2 m m^{-2} a^{-1}, which is about one third to half of the average annual ice loss rate over the 20th century (Zemp et al. 2015) and is good enough for validation of glaciological series (Zemp et al. 2013)
			T		
Standards and References	Huss, M. (2013). Density assumptions for converting geodetic glacier volume change to mass change. The Cryosphere, 7(3), 877–887. http://doi.org/10.5194/tc-7-877-2013 Joerg, P. C., & Zemp, M. (2014). Evaluating Volumetric Glacier Change Methods Using Airborne Laser Scanning Data. Geografiska Annaler: Series A, Physical Geography, 96(2), n/a-n/a. http://doi.org/10.1111/geoa.12036 Zemp, M., Thibert, E., Huss, M., Stumm, D., Rolstad Denby, C., Nuth, C., Nussbaumer, S.U., Moholdt, G., Mercer, A., Mayer, C., Joerg, P.C., Jansson, P., Hynek, B., Fischer, A., Escher-Vetter, H., Elvehøy, H., and Andreassen, L.M. (2013): Reanalysing glacier mass balance measurement series. The Cryosphere, 7, 1227-1245, doi:10.5194/tc-7-1227-2013. Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., … Vincent, C. (2015). Historically unprecedented global glacier decline in the early 21st century. Journal of Glaciology, 61(228), 745–762. http://doi.org/10.3189/2015JoG15J017 Xu, C., Li, Z., Li, H., Wang, F., & Zhou, P. (2018). Long-range terrestrial laser scanning measurements of summer and annual mass balances for Urumqi Glacier No. 1, eastern Tien Shan, China. The Cryosphere Discussions, 1-28. doi: 10.5194/tc-2018-128.					

Table 5: GCOS requirements for ice sheet ice velocity. Codes are: G = goal, the ideal requirement, B = breakthrough, a requirement leading to significant improvement in current datasets, T = threshold, the minimum requirement for useful data.

Name	Ice Velocity				
Definition	Surface-parallel vector of the surface ice flow.				
Unit	m y^{-1} (average speed in grid cell of surface ice flow)				
Note					
Requirements					
Item needed	Unit	Metric	[1]	Value	Notes
Horizontal Resolution	m	Grid cell size	G	50	
			B	100	
			T	1000	
Vertical Resolution			G	-	N/A. One value per point of Earth's surface.
			B	-	
			T	-	
Temporal Resolution	month	time	G	1	
			B		
			T	12	
Timeliness			G		
			B		
			T		
Required Measurement Uncertainty	m y^{-1}	error of measured in-situ using the geodetic method and remotely sensed surface elevation	G	10	
			B	30	
			T	100	
Stability	m s^{-1}	as above	G		
			B		
			T	10	
Standards and References	Hvidberg, C.S., et al., 2021. User Requirements Document for the Ice_Sheets_cci project of ESA's Climate Change Initiative, version 1.5, 03 Aug 2012.				

Table 6: GCOS requirements for the area covered by snow (Snow ECV). Codes are: G = goal, the ideal requirement, B = breakthrough, a requirement leading to significant improvement in current datasets, T = threshold, the minimum requirement for useful data.

Name	Area Covered by Snow				
Definition	Snow cover refers to the % coverage solid surface (ground, ice sea ice, lake ice, glaciers, etc) in open areas and on top of vegetation cover that is present, such as forest canopies covered by snow at a given time. Sometimes called "viewable snow".				
Unit	km^2				
Note	Area covered by snow is observed in-situ and by satellite (Robinson, 2013; Frei et al., 2012). The visible satellite identifies the snow cover with few millimeters of snow depth. The microwave radiometer can detect at first from few centimeters of snow depth.				
Requirements					
Item needed	Unit	Metric	[1]	Value	Notes
Horizontal Resolution	m	Size of grid cell	G	50	
			B	500	
			T	1000	
Vertical Resolution			G	-	N/A
			B	-	
			T	-	
Temporal Resolution	h	Frequency of measurement	G	6	
			B	24	
			T	48	
Timeliness	h		G	3	
			B	24	
			T	240	
Required Measurement Uncertainty (2-sigma)	%		G	5	
			B	15	
			T	20	
Stability	%		G	1	
			B	5	
			T	10	
Standards and References	Frei, A., Tedesco, M., Lee, S., Foster, J., Hall, D. K., Kelly, R. and Robinson, D. A. (2012): A review of global satellite-derived snow products, Advances in Space Research, 50, 1007–1029. Goodison, B. and Walker, A. (1994): Canadian development and use of snow cover information from passive microwave satellite data, B. Choudhuly et al. (ed), Passive Microwave Remote Sensing of Land-Atmosphere Interaction, Utrecht: VSP BV, 245-262. Robinson, D.A. (2013): Climate Data Record Program (CDRP): Climate Algorithm Theoretical Basis Document (C-ATBD) Northern Hemisphere Snow Cover Extent, CDRPATBD-0156. Asheville, North Carolina, USA 28 pp. Sturm, M., Taras, B., Liston, G. E., Derksen, C., Jonas, T. and Lea, J. (2010): Estimating Snow Water Equivalent Using Snow Depth Data and Climate Classes. Jour. Hydromet. 11, 1380-1394. Bormann, K., R. Brown, C. Derksen, and T. Painter. 2018. Estimating snow cover trends from space. Nature Climate Change. DOI: 10.1038/s41558-018-0318-3.005 WMO (2018), Guide to instruments and methods of observation: Volume II - Measurement of Cryospheric Variables, 2018th ed., World Meteorological Organization, Geneva, Switzerland, 52 pp. Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K., and Sokratov, S.A. (2009): The International Classification for Seasonal Snow on the Ground, UNESCO-IHP, Paris, France, viii+80 pp.				

3.1.2 GCW (formerly IGOS/GTOS)

The findings of IGOS are summarised in the IGOS Cryosphere Theme Report of 2007 [5], which has also requirements for glaciers in its Table B6, reproduced as Table 6 below. Its current requirements are laid out in [12] and used as the basis for the World Meteorological Organisation Observing Systems Capability Analysis and Review Tool (WMO OSCAR) [13]. For the glacier area (outlines) product, however, we follow the target requirements listed in [6] (GCOS 2011).

Relevant requirements: URq_01 (area), URq_02 (elevation change), URq_03 (velocity)

Table 6: IGOS requirements for glaciers. Codes are: C = current capability, T = threshold requirement (minimum necessary), O = objective requirement (target), L = low end of measurement range, U = unit, H = high end of measurement range, V = value

Parameter	COT	Measurement Range			Measurement Accuracy		Resolution				Comment or Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Area	C				1	%	5	m	30	yr	airborne
	O				3	%	30	m	5	yr	Landsat etc.
	T	0.01		km²	3	%	50	m	5	yr	Hi-res optical
	O	0.01		km²	1	%	15	m	1	yr	
Topography	O										Airborne
	C	0	8500	m sl.	5	m	100	m	5	yr	For models
	T	0	8500	m sl.	0.1	m	30	m	1	yr	Mass balance
Velocity	O				1	%	point		1	yr	In situ
	C	0	10	km/yr	5	%	10	m	1	yr	InSAR, hi-res optical, etc.
	T	0	10	km/yr	1	%	20	m	1	mo	
Glacier dammed lakes	O				1	%	1	m	1	yr	airborne
	C	0.05	10	km²	3	%	50	m	1	mo	SAR, hi-res optical
	T	0.01	10	km²	1	%	15	m	5	day	
Facies, snowline	C						point				In situ
	T			class	200	m	100	m	1	mo	Position of boundary
	O			class	30	m	30	m	10	day	
Accumulation	C				5	%	point				In situ
	T	0.05	8	m	10	%	500	m	1	yr	Ku-, X-SAR
	O	0.10	5	m	5	%	100	m	1	mo	
Mass balance	C				0.10	m	point				In situ
	T	0	±5	m	0.20	m	500	m	1	mo	process model & SAR
	O	0	±5	m	0.05	m	100	m	1	yr	
Ice thickness	C	0	200	m	2-5	m	100	m	30	yr	In situ, airborne

3.1.3 CRG

The climate research group (CRG) advising CCI+ has not yet forwarded requirements that are different from those listed in Table 7. However, the former CRG of Glaciers_cci had an important requirement that is unsolved, the increase in the consistency of the glacier outlines timestamps. This work is now addressed for the ECV Glaciers in the related C3S project and thus no longer considered here.

3.1.4 CMUG

CMUG provides technical feedback to all CCI projects. The most recent CMUG user survey [11], launched in 2019, recommended using the pre-existing requirements made by GTN-G.

3.1.5 GTN-G

The science bodies WGMS, GLIMS and NSIDC form the global terrestrial network for glaciers (GTN-G) that is responsible for co-ordinated global glacier monitoring. Their website [8] lists guideline publications for creating and submitting glacier data as well as the documents from international organisations that provide recommendations and requirements for satellite-based cryospheric monitoring (e.g. GCOS, GCW). The three requirements below describe to where results for the three main products (glacier outlines, elevation changes, velocity) should be submitted.

Relevant requirements: URq_08, URq_09 and URq_10

3.1.6 IACS working group on the RGI

The RGI working group was granted a 4-year extension by IACS in 2020. Specific requirements (glacier outlines production in specific regions) resulted for C3S rather than Glaciers_cci+. There are thus no changes of requirements form this working group.

3.1.7 Cross-CCI activities

There has been collaboration between Glaciers_cci and several other CCI projects (see Table 2), in particular Land Cover CCI has been provided with glacier outlines, and Antarctic Ice Sheets and Greenland Ice Sheets have shared regional definitions (discriminating the ice sheet from the peripheral glaciers), scientific methods and team members. Moreover, Glaciers_cci has contributed to the cross-ECV project on Sea Level Budget Closure. These collaborations are continuing in CCI+, and extend to more recent ECVs Permafrost and Snow.

Relevant requirements: URq_21 (from Permafrost) [10]

3.2 Requirements from a Research Perspective

The IPCC is the United Nations body for assessing the science related to climate change. It prepares periodic reports, identifying areas of agreement within the scientific community, and areas where further research is needed. Its fifth assessment report was published in 2013/14 (IPCC AR5), and sixth in 2021 (IPCC AR6). In September 2019 the IPCC published a Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC).

3.2.1 IPCC – AR5 and AR6 (WG I: Physical science basis)

As part of the AR5 Working Group I reports on 'The Physical Science Basis' [7], a number of issues relating to the current state of observations of glaciers and ice caps were raised. Key issues relevant to Glaciers_cci were:

- The largest uncertainty in estimates of mass loss from glaciers comes from Antarctica. Section 4.3.3 of the main report indicates that this is because there is not currently a comprehensive inventory for the peripheral glaciers and ice caps of Antarctica, only those on the Antarctic and the Sub-Antarctic Islands.
- The certainty of global glacier area estimates is limited by regional variability in the accuracy of glacier outlines, the minimum size of glaciers included and the subdivision of contiguous ice masses.
- Differing time spans covered by different area change measurement studies leads to uncertainty in generating regional or global scale estimates of area change.

The more regional scope of Glaciers_cci+ with respect to Glaciers_cci means that the points above are no longer relevant to this project. However, they will be addressed within C3S.

AR6's equivalent report, where the cryosphere is discussed in chapter 9 [14], acknowledges improvements to the RGI since AR5. AR6 used version 6, while AR5 used version 2. The emphasis in AR6 is on understanding regional and global patterns of glacier evolution, which fits well with the case studies approach used within Glaciers_cci+. AR6 also states (page 1278) 'Secondary processes such as ... surges or glacier collapse ... are not represented in global glacier models, resulting in both underestimated and overestimated sensitivity to warming that is currently not possible to quantify.' Our focus on investigating dynamically unstable glaciers is thus also in line with this requirement.

AR6 introduces the Climate Impact-Driver (CID) framework for assessment, where a CID is defined as the physical climate system conditions (e.g., means, events, and extremes) that affect an element of society or ecosystems. CIDs are inventoried in Ruane (2022), where glaciers are included in the 'snow and ice' type, category 'snow, glacier and ice sheet'. The brief description of this CID is 'Snowpack seasonality and characteristics of glaciers and ice sheets including calving events and meltwater'. It acknowledges that in AR6's assessment of climate change services there is no one-size-fits-all specification of climate services (AR6 section 12.6.2), and does not give numerical targets for glacier research.

3.2.2 IPCC – SROCC

This report [9] was released on 25/09/2019. It focuses on high mountain areas (Chapter 2) and polar regions (Chapter 3). Rather than providing specific requirements, which IPCC shall not give, it recommends cross-disciplinary collaboration and identifies key gaps in knowledge.

For mountains, page 2-57 lists several knowledge gaps and problem areas that are relevant for Glaciers_cci +, such as that "Earth observation satellites … still face challenges for observations in mountains such as dealing with cloud cover and rugged terrain" and "… observational knowledge gaps currently impede efforts to quantify trends, and to calibrate and validate models that simulate the past and future evolution of the cryosphere and its impacts.". Error bars for glacier mass losses are still quite high, e.g. for HMA -150 ± 100 kg m^{-2} yr^{-1} (p. 2-3).

"There is a need to better understand the evolution of polar glaciers and ice sheets, and their influences on global sea level. Longer and improved quantifications of their changes are required, especially where mass losses are greatest, and (relatedly) better attribution of natural versus anthropogenic drivers." (page 3-98)

Apart from the last point (attribution), the above knowledge gaps will be addressed in Glaciers_cci+ by investigating glacier mass changes in polar regions and in HMA. Observational techniques will be improved to prolong time series, and fill spatial and temporal gaps.

3.2.3 Scientific literature

Our thematic focus on the investigation of dynamically unstable glaciers in the Arctic and HMA is also motivated by the scientific literature. Numerous recent studies have demonstrated the possibilities of remote sensing data not only for detecting glacier surges (Rankl et al. 2014, Bhambri et al. 2017, Strozzi et al. 2017, Chudley and Willis 2018), but also providing a better understanding of the responsible physical mechanisms (e.g. Dunse et al. 2015, Nuth et al. 2019, Quincey et al. 2015, Paul et al. 2017, Round et al. 2017, Sevestre e al. 2015, Wendt et al. 2017, Willis et al. 2018). In general, the latter are based on observations of changes in elevation and/or flow velocities at high spatial and temporal resolution. This also applies to recent glacier collapses in Tibet that have been observed and interpreted using such data (e.g. Kääb et al. 2018, Gilbert et al. 2018, Paul 2019).

Two overview studies by Qiu (2015 and 2017) summarise several of the mysteries of dynamically unstable glaciers. A most critical scientific point to be solved according to these overviews is the possible impact of climate change on glacier surges and collapses. This is somewhat beyond the scope of the Glaciers_cci+ project, as it also requires the analysis of climate model data (re-analysis) and application of numerical modelling (e.g. surface mass balance).

David Molden, director general of ICIMOD until 2020, is cited in Qiu (2015) with the point: "There is an urgent need to understand what's happening with Karakoram glaciers ... It's critical for planning policies and infrastructures and adapting to climate change." This is in line with the request forwarded in the global overview study by Sevestre and Benn (2015) who are asking for more detailed regional studies to further explore and refine their enthalpy cycle model. The Glaciers_cci+ project aims at further contributing to these two points.

ICIMOD issued a book assessing the needs of the Himalayan region related to climate change (Wester et al., 2019). Its Chapter 8 provides specific recommendations to the cryosphere:

- Develop estimates of glacier mass change prior to 2000, which are currently missing in many regions, using declassified stereo imagery
- Collect field-based measurements of glacier thickness and debris thickness (e.g. by ground-penetrating radar (GPR)) in representative glacier regions to evaluate glacier volume estimates and debris cover characteristics
- Develop and test physically based and empirical models of debris-covered glacier melt components that include heat conduction through debris, ice cliff backwasting, and supraglacial ponds, and scale up to larger glacierized regions
- Develop fully coupled ice flow models taking debris sources, transport and deposition into account
- Model intercomparison projects to assess different sources of uncertainty: initial conditions, forcing data, and model structures

The first recommendation, that of estimating historical glacier change, is a priority for Phase 2 of the Glaciers_cci+ project. Phase 1 of the Glaciers_cci+ project produced 20 journal papers [17], advancing the body of scientific literature.

3.2.4 Glaciers_cci user survey

The Glaciers_cci project sent questionnaires to members of the GLIMS and Cryolist mailing lists, as detailed in [2]. During the course of the project, two main requirements were derived. As one is already implemented (use of UTM projection), we kept only one requirement.

Relevant requirements: URq_15.

3.2.5 Glaciers_cci+ project goals

The project is subject to the requirements of ESA's CCI programme as a whole, which specified high-level cardinal, programmatic, general, technical and management requirements in the updated Statement of Work [18] issued for CCI+ phase 2. There are 23 in total, laid out in full in Annex B for glaciers. Those relevant to the user experience are summarised here:

[TR-4] The Glaciers ECV Products delivered by Glaciers_cci+ shall include:

- Glacier products derived from optical, radar and altimetry (lidar & radar) instruments.

All products shall:

- cover the Arctic and High Mountain Asia.
- focus on new satellite missions selected in [TR-6]
- where appropriate, include monthly, seasonally and annually aggregated versions

[TR-5] The contractor shall include satellite missions selected in [TR-6]

[TR-6] The Glacier ECV products shall be derived from the following missions:
1. Landsat 9 (2021 – present and continuing)
2. MSI on board Sentinel-2A and B (2016 – present and continuing)
3. Hexagon/Corona on board Keyhole (1960 – 1990)
4. SRAL on board Sentinel-3A (2016 – present and continuing)
5. SRAL on board Sentinel-3B (2018 – present and continuing)
6. ICESat-2 (2019 – present and continuing)
7. SAR on board ERS-1 and ERS-2 (1991 – 2010)
8. SAR on board Envisat (2002 – 2012)
9. SAR on board Sentinel-1A (2014 – present and continuing)
10. SAR on board Sentinel-1B (2016 – 2021)

[TR-7] Where appropriate, the contractor shall take advantage of the following missions to improve the Glacier velocity algorithms:
- SAOCOM (2020 – present and continuing)
- ICEYE (2014 – present and continuing)

[TR-8] The performance of new sensors shall be investigated compared to other products (including those developed in Glaciers_cci+ Phase 1)

[TR-9] All products shall include a full end-to-end uncertainty characterisation

[TR-10] There shall be no duplication of data production between Copernicus and CCI and the algorithm improvements shall be coordinated with Copernicus Services (C3S) such that the quality and uptake from CCI into C3S is ensured.

[TR-11] ECV data sets generated within CCI shall be reported to and catalogued by the CEOS ECV Inventory

[TR-12] DOI's shall be assigned to all ECV data sets made publicly available

The project has been designed with these requirements in mind. Scientifically interesting regions beyond the major ice sheets have been selected for study [TR-4], using long-term data streams from the satellites listed in TR-6 and TR-7. Participating groups work for both C3S and CCI, which assures co-ordination between services [TR-10]. TR-10 to TR-12 will be respected. The key regions from TR-4 are given in the introduction to this document (Section 1.1). The Arctic and High Mountain Asia are continued from phase 1. A further region, the Greenland Periphery, has been added for Phase 2.

As one of the key goals of the project is to compare data from a range of sensors, it is essential to develop merged data products from the start. This leads to a new requirement, URq_20.

Since the start of the CCI projects, the ice velocity community have refined their techniques so that it is possible to make products at weekly resolution, denser than that required by IGOS in part of URq_03. This gives rise to a new requirement, URq_22.

Relevant requirements: URq_20, URq_22.

4. User Requirements Feasibility

The following subsections highlight and revise the feasibility of user requirements that fall within the scope of the Glaciers CCI+ project. Surface elevation change is derived by two different techniques, digital elevation model (DEM) differencing and altimetry, with different capabilities, so they are treated separately.

4.1 Glacier outlines

Whereas two of the requirements are feasible (**URq_01** and **URq_09**), **URq_05** requires further work and the feasibility of the various issues remains to be seen. **URq_21** is difficult to achieve and will likely be addressed in C3S rather than Glaciers_cci+. The overarching **URq_20** however, should be feasible as data combination is a major aim of the project.

4.2 Elevation change – DEM differencing

All URq related to SEC from DEM differencing are in principle feasible, but feasibility of **URq_02** is spatially variable depending on data availability. Suitable coverage by elevation data, or raw data from which DEMs can be produced, varies. For instance, ASTER data and derived DEMs are impacted by frequent cloud cover and spatially non-continuous acquisition plans, similar for DigitalGlobal stereo acquisitions, which are used for the ArcticDEM and the High Mountain Asia DEM. DEMs from radar interferometry (SRTM, TanDEM-X WorldDEM) are affected by radar penetration. Over large areas URq_02 should be feasible, but there will be zones of exception due to data availability and quality.

4.3 Elevation change – altimetry

For SEC measurements from altimetry we identify the following user requirement that is not fully feasible:

- **URq_02:** GCOS target requirement for horizontal resolution of SEC measurements of 30-100 m. This resolution is not achievable with altimetry due to the constraints of the sensors and the methods necessary for deriving elevation change measurements. The typical SEC resolution that can be reliably achieved from altimetry is 1– 5 km depending on data recovery and geographical region. By design, space-borne altimetric data follow orbit tracks, and are thus not evenly distributed.

4.4 Ice velocity

For IV measurements we identify the following user requirement that is not fully feasible:

- **URq_03:** The IGOS/GTOS requirement for horizontal resolution of IV measurements of 20 m spatial resolution. This resolution is generally not achievable due to the constraints of the sensors and the methods necessary for deriving velocity. The primary sensor for deriving ice velocity is Sentinel-1 (S1) SAR. The typical IV resolution that can be reliably achieved from SAR data is 100–250 m depending on the coherence between image pairs. A goal in this project is development to improved spatial resolution using S1 (towards ~100 m pixel spacing). Velocity from optical data such as from Sentinel-2 will have better spatial resolution (~ 50 m pixel spacing) but are less complete in space and time due to cloud cover and polar night.

5. Summary of requirements and uncertainty targets

The final requirements, once unfeasible and obsolete requirements are removed, are summarised in Table 7 below. For each user requirement, the source and the type of work it will address are identified. Background (BG) means that this is a continuous activity, selection (S), production (P), and dissemination (D) mean that the related requirement has to be considered during data selection, production, and dissemination, respectively. Surface elevation change methodologies are split into two, DEM differencing (SEC-DD) and altimetry (SEC-ALT). The requirements are grouped by the parameter they refer to, and repeated where applicable to multiple parameters.

Table 7: Summary of requirements and uncertainty targets. GCOS target levels given in square brackets where appropriate, where G = goal, the ideal requirement, B = breakthrough, a requirement leading to significant improvement in current datasets, T = threshold, the minimum requirement for useful data

ID	Parameter	Requirements	Source	Type	Notes
URq_01	GO	15-30 m horizontal resolution [G-B], annual temporal resolution (at end of ablation season) [G], better than 5% accuracy [B].	GCOS	BG	As for CCI, selected to apply to typical glacier mapping sensors
URq_05	GO	Greater consistency is required in inventories (e.g. methods for subdivision of glacier complexes, consideration of seasonal snow, identification of debris-covered glaciers).	IPCC	P	As in CCI
URq_09	GO	Provide GO data to the GLIMS database in the required format.	GTN-G	D	As in CCI
URq_21	GO	Better distinguish debris-covered glaciers from rock glaciers.	Permafrost CCI+	BG	New to CCI+, might be covered by C3S
URq_02	SEC	30-100 m horizontal [G] and 1 m vertical resolution [between G and B], decadal temporal resolution [T], accuracy better than 2 m/decade [B, no G given], 1 m/decade stability [better than B, no G given]	GCOS	BG	As in CCI+ phase 1, tailored to SEC-DD. Horizontal resolution is unfeasible for SEC-ALT.
URq_08	SEC	Provide SEC data to the WGMS database	GTN-G	D	As in CCI
URq_15	SEC-ALT	Produce seasonal and annual SEC product	Glaciers_cci user survey	P	As in CCI
URq_16	SEC	Deliver SEC product in UTM projection	Glaciers_cci user survey	D	As in CCI
URq_03	IV	20 m horizontal resolution, monthly to annual resolution, and better than 1% accuracy.	IGOS/GTOS	BG	As in CCI, horizontal resolution is unfeasible
URq_10	IV	Provide velocity data to the GLIMS database	GTN-G	D	As in CCI
URq_22	IV	Weekly resolution	Glaciers_cci+	BG	New to CCI+
URq_20	GO, SEC, IV	A combined data product should be made	Glaciers_cci+	D	New to CCI+

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Abbreviations

C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CEOS	Committee on Earth Observation Satellites
CMUG	Climate Modelling User Group
CRG	Climate Research Group
DEM	Digital Elevation Model
DOI	Digital Object Identifier
ECV	Essential Climate Variable
ESA	European Space Agency
GCOS	Global Climate Observing System
GCW	Global Cryosphere Watch
GLIMS	Global Land Ice Measurements from Space
GO	Glacier Outline
GTN-G	Global Terrestrial Network for Glaciers
GTOS	Global Terrestrial Observing System
HMA	High Mountain Asia
IACS	International Association of Cryospheric Sciences
ICIMOD	International Centre for Integrated Mountain Development
IGOS	Integrated Global Observing Strategy
IMBIE	Ice sheet Mass Balance and Intercomparison Exercise
IPCC	Intergovernmental Panel on Climate Change
IV	Ice Velocity
NSIDC	National Snow and Ice Data Centre
RAGMAC	Regional Assessments of Glacier Mass Change
RGI	Randolph Glacier Index
SEC	Surface Elevation Change
SROCC	Special Report on the Ocean and Cryosphere in a Changing Climate
TOPC	Terrestrial Observation Panel for Climate
URD	User Requirements Document
WG	Working Group
WGMS	World Glacial Monitoring Service
WMO	World Meterological Organisation
WMO OSCAR	World Meterological Organisation Observing Systems Capability Analysis and Review Tool