User Requirement Document (URD)

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LIST OF ITEMS TO BE CONFIRMED OR DEFINED

Not applicable

APPLICABLE DOCUMENTS

None

REFERENCE DOCUMENTS

CMUG, 2022. Deliverable 3.1 - Quality assessment Report (Sept. 2022).

Global Climate Observing System programme (GCOS), 2022. The 2022 ECVs Requirements.

Global Climate Observing System programme (GCOS), 2022. The GCOS 2022 Implementation Plan.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

1 Executive summary

This document summarises the first updated version of user requirements for the Essential Climate Variable (ECV) 'Lakes', collected within Phase 2 of the European Space Agency's Lakes Climate Change Initiative (CCI) (Lakes_cci) (http://cci.esa.int/lakes).

This report synthesises information obtained through (1) review of existing reference documents and scientific literature, (2) 2022 CMUG Integration and Colocation meetings and related documents (https://climate.esa.int/en/events/12th-cci-colocation-meeting/), and (3) the wider lakes research community, including results from a new survey (https://climate.esa.int/en/projects/lakes/news-and-events/news/third-users-survey/). Major updates with respect to the previous version of this deliverable (User Requirement Document - URD v2) produced during Phase 1 of the project are based on the new GCOS and IPCC documents, interaction between Lakes_cci and the climate modelling community (CMUG), as well as on the results gathered from the third survey.

The GCOS requirements for Lakes ECV were recently revised (GCOS-245) and are now considered more feasible by the consortium. At the same time, Assessment report 6 (AR6) of WGI of the IPCC emphasizedthe importance of Lakes ECVs in improving knowledge on the carbon and methane budget, water cycle and energy budgets. CMUG interaction evidenced the capabilities and the current limitation of the Lakes_cci dataset (with surface temperature and ice cover variables used for regional climate modelling). User consultation further illustrated the science disciplines interested in the Lakes ECV while collecting user needs regarding data pre-processing, accessibility of sub-sets of the dataset, and observing a larger number of lakes at sufficient frequency. Technical support (e.g., script, tools, tutorial) to exploit the data successfully is also welcomed. The climate data record (CDR) v2 was published in July 2022 so that the collected requirements may not yet be fully representative of the collective experience of the user community using this latest version. With a major uptake in use of Lakes_cci data, we expect increasing exploitation of these data records, which should lead to further feedback on product requirements.

2 Overview

Lakes and inland seas are integrators of environmental and climatic changes occurring within their catchments. Factors driving lake condition vary widely across space and time, and lakes, in turn, play an important role in local and global climate regulation, with positive and negative feedback depending on the catchment. Understanding the complex behaviour of lakes in a changing environment is essential to effective water resource management and mitigation of climate change effects. Lakes integrate responses over time and studies of globally distributed lakes can capture different aspects of climate change. Lakes are of significant interest for the scientific and environmental communities. Different disciplines, such as hydrology, limnology, climatology, and biogeochemistry are interested in the millions of lakes (from small ponds to inland seas) from local to global scale.

Therefore, a global and consistent climate data record of lakes is essential to mitigate and adapt to climate change. The Lakes_cci project develops satellite-derived products for the Lakes ECV, as defined by GCOS-244:

- Lake Water Level (LWL): fundamental to understand the balance between water inputs and water loss.
- Lake Water Extent (LWE): a proxy for change in glacial regions (lake expansion) and drought in many arid environments, water extent relates to local climate for the cooling effect that water bodies provide.
- Lake Surface Water temperature (LSWT): correlated with regional air temperatures and a proxy for mixing regimes, driving biogeochemical cycling and seasonality.
- Lake Ice Cover (LIC): freeze-up in autumn and advancing break-up in spring are proxies for gradually changing climate patterns and seasonality.
- Lake Ice Thickness (LIT): a driver of seasonal lake biogeochemistry and early indicator of changing lake thermodynamics. This product is being evaluated and upscaled during the current project phase.
- Lake Water-Leaving Reflectance (LWLR): a direct indicator of biogeochemical processes and habitats in the visible part of the water column (e.g., seasonal phytoplankton biomass fluctuations), and an indicator of the frequency of extreme events (peak terrestrial run-off, changing mixing conditions).

The principal objective of the Lakes project is to produce and validate a consistent data set of the variables grouped under the Lakes ECV. This includes aiming for the longest period of combined satellite observations by designing and operating processing chains, designed to ultimately feature in a sustainable production system. A challenge is to establish wide uptake by a varied and fragmented landscape of potential users. This requires significant alignment of current practices for producing the individual lake variables, cross-variable validation, and demonstration in the form of use cases.

This is the latest update of the User Requirements Document (URD) for the ESA Climate Change Initiative Lakes ECV project (Lakes_cci). The user requirements describe the needs of targeted users of climate data records (CDRs) of variables describing the state of lakes for climate applications. The main objective is to document the user requirements in climate science and climate services for which the ECV products are primarily developed.

The updated requirement analysis takes into account the latest GCOS implementation plan updates GCOS-244 and GCOS-245 (2022a, b) and the outcome of the GCOS public consultation on ECV requirements, together with feedback from its panels (Atmospheric Observation Panel for Climate - AOPC, Ocean Observations Physics and Climate Panel - OOPC, Terrestrial Observation Panel for Climate - TOPC; https://climate.esa.int/en/events/12th-cci-colocation-meeting/). In addition, the analysis will consider the priorities of international climate assessments, such as IPCC WG1, relevant CMUG outputs and specific user requests for ECV data products (e.g., model intercomparison exercises, climate services). All climate-relevant applications of the ECV will be considered, together with the discussion with other CCI projects to ensure the consideration of requirements for cross-ECV consistency.

The structure of the document is as follows:

Requirements from existing reference documents are reviewed in section **Erreur ! Source du renvoi introuvable.** (GCOS and IPCC WG1). This section also focuses on the interaction between Lakes_cci and CMUG.

Section 4 reports requirements from the lake community. This section illustrates the results obtained by circulating the third survey, provides an overview of requirements from scientific literature, and summarizes the dissemination activities of the project. A preliminary user and applications section is also included.

Section 5 provides conclusions and recommendations for future work.

3 Requirements from existing documents

This section reports on requirements from existing international reference documents. Sub-sections address the international context (GCOS, IPCC WG1), and requirements from the CCI Climate Modelling Group (CMUG).

3.1 Requirements from international reference documents

3.1.1 Requirements from Global Climate Observing System (GCOS)

The Global Climate Observing System (GCOS) is a joint programme of the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), the United Nations Environment Programme (UNEP), and the International Science Council (ISC). It assesses the status of global climate observations of the atmosphere, land and ocean and produces guidance for its improvement.

GCOS serves a broad range of user needs for globally coordinated climate observations. Its goal is to provide comprehensive data and climate information on the total climate system, including a range of physical, chemical and biological properties, along with atmosphere, oceanic, hydrological, cryosphere and terrestrial processes. GCOS works with existing or planned operational and research programmes for acquiring, storing and distributing systematic global climate data and identifies gaps in observations, data management and information distribution systems. GCOS identifies user data needs to enable the further development of these programmes to ensure continuity and diversification of climate observations. Data needs are organized around the concept of ECVs which include physical, chemical and biological properties that are essential to describe the climate system. An ECV product, is a measurable parameter needed to characterize the ECV. Data for these ECVs helps to support the UNFCCC, with satellites providing observations for around two-thirds. The observations supported by GCOS contribute to solving challenges in climate research. They also underpin climate services and adaptation measures.

The latest GCOS implementation plan (GCOS-244, 2022a,) outlines the practical actions needed and gaps to be addressed over the coming decade to provide the actionable climate information for mitigation, early warning systems to help tackling the climate crisis, as well as information relating to the risks and attribution of extreme events.

ECVs can be used to guide mitigation and adaptation measures, to assess climate risks, to attribute climatic events to underlying causes, and to support climate services. Climate modellers use ECVs to study drivers, interactions and feedbacks due to climate change, as well as teleconnections, tipping points, and fluxes of energy, water, carbon, and to predict future change.

Systematic observation of the Earth climate is the fundamental basis upon which the UNFCCC was founded, and the Paris Agreement adopted. GCOS currently specifies 54 ECVs, of which around 60 percent can be addressed by satellite data. Satellite observations are unique in providing global coverage and time series of consistent observation. The ESA CCI exploits the full satellite archive to develop the scientific basis and produce data records of the 23 ECVs plus precursors on river discharges and other long-lived GHGs (Greenhouse Gases) that cover the whole world and stretch back more than thirty years.

The 2022 Implementation Plan (IP2022) specifies 6 themes and issues for Actions:

- Theme A - Ensuring Sustainability: addressing in situ and satellite observations that are currently at risk.
- Theme B - Filling Data Gaps: observations are consistently deficient in parts of Africa, South America, Southeast Asia, the deep oceans and polar regions.

- Theme C - Improving data quality, availability and utility, including reprocessing, improvements in transforming observations into user-relevant information.
- Theme D - Managing Data: ensuring data is well-curated, discoverable, open and freely available and permanently archived
- Theme E - Engaging with Countries: coordinating national efforts with global systems and support, understanding national needs.
- Theme F - Other Emerging Needs: some new needs can already be identified and addressed (e.g. for adaptation and mitigation)

Lakes are specifically addressed in “Action B5: Implementing global hydrological networks”. Between the activities, the improvement of the collection of hydrological observations is mentioned, which is mainly on rivers and groundwater, but it also foresees an increase in the contribution of in situ water level observations of lakes and reservoirs to the International Data Centre on Hydrology of Lakes and Reservoirs (HYDROLARE). It is also reported that the current database of lake levels is incomplete. This is linked to actions B2 “Development and implementation of the Global Basic Observing Network (GBON)” which can contribute to the implementation of B5 and B10 “Identify gaps in the climate observing system to monitor the global energy, water and carbon cycles” for the closure of the water cycle.

The “2022 GCOS ECVs Requirements” (GCOS-245) is a supplement document and presents the updated list of ECVs requirements.

The ECV framework has evolved since the publication of the previous list of ECVs requirements in the GCOS IP 2016. The list of ECVs and ECVs products has changed as well as reported in the new document “2022 GCOS ECVs Requirements”. Three specific tables were produced for Atmosphere, Ocean and Terrestrial variables. A sample of the terrestrial ECVs is reported in Figure 1 for freshwater: no significant changes are reported for Lakes ECV.

Terrestrial		
ECV	**ECV Product 2016**	**ECV Product 2022**
Groundwater	Groundwater Volume Change	Groundwater Storage Change
	Groundwater Level	Groundwater Level
	Groundwater Recharge	
	Groundwater Discharge	
	Wellhead Level	
	Water Quality	
Lakes	Lake Water Level	Lake Water Level (LWL)
	Water Extent	Lake Water Extent (LWE)
	Lake Surface-Water Temperature	Lake Surface Water Temperature (LSWT)
	Lake Ice Cover	Lake Ice Cover (LIC)
	Lake Ice Thickness	Lake Ice Thickness (LIT)
	Lake Colour (Lake Water-Leaving Reflectance)	Lake Water-Leaving Reflectance
River Discharge	River Discharge	River Discharge
	Water Level	Water Level
	Flow Velocity	
	Cross-Section	

Figure 1. Sample of the Essential Climate Variables (ECVs) changes from IP2016 to IP2022 for freshwaters.

The requirements are expressed in terms of five criteria: i) spatial resolution - horizontal and vertical (if needed); ii) temporal resolution (or frequency) – the frequency of observations e.g., hourly, daily or annual; iii) measurement uncertainty – the parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand; iv) stability – the change in bias over time, and quoted per decade; v) timeliness - the time expectation for accessibility and availability of data.

Moreover, for each of these criteria, a goal, breakthrough and threshold value are presented:

- Goal (G): an ideal requirement above which further improvements are not necessary.
- Breakthrough (B): an intermediate level between threshold and goal which, if achieved, would result in a significant improvement for the targeted application. The breakthrough value may also indicate the level at which specified uses within climate monitoring become possible. It may be appropriate to have different breakthrough values for different uses.
- Threshold (T): the minimum requirement to be met to ensure that data are useful.

The requirements for the Lakes ECVs and their products are presented below in Table 1,Table 2, Table 3,
Table 4, Table 5, and Table 6.

Table 1. Lake Water Level (LWL) ECV product requirements.

Name	Lake Water Level (LWL)				
Definition	Lake Water Level (LWL). Elevation of the free surface of a lake relative to a specified vertical datum.				
Unit	cm				
Note					
Requirements					
Item needed	Unit	Metric	[1]	Value	Notes
Horizontal Resolution	m		G	-	In situ observation by a point measurement on gauge
			B	-	
			T	100	
Vertical Resolution			G	-	N/A
			B	-	
			T	-	
Temporal Resolution	d		G	1	
			B	30	
			T	365	Annual summary in the form of yearbook
Timeliness	d		G	1	In some case it can be interesting to have near real time lake level changes (in case of extreme events)
			B	30	
			T	365	For yearbooks
Required Measurement Uncertainty (2-sigma)	cm		G	5	
			B		
			T	10	Allows to use the considered characteristic in global and regional climate models
Stability	cm /decade		G	1	
			B		
			T	10	Allows to use the considered characteristic in global and regional climate models
Standards and References	Technical Regulations, volume III, Hydrology, 2006 edition, WMO-No.49 Guide to Hydrological Practices, sixth edition,2008, WMO-No.168				

Table 2. Lake Water Extent (LWE) ECV product requirements.

Name	Lake Water Extent (LWE)				
Definition	Areal extent of the surface of a lake.				
Unit	km²				
Note	LWE is only measurable using satellite imagery. For shallow lakes the LWE variable is more relevant than the Lake Water Level to detect climate change signal (Mason et al., 1994).				
Requirements					
Item needed	Unit	Metric	[1]	Value	Notes
Horizontal Resolution	m		G	10	Using Sentinel-2 missions. Allows to determine small extent variations.
			B	30	Using Landsat (5,7,8) missions. Still relevant for shallow lakes with high extent potential variations.
			T	1000	Useful to partition surface energy fluxes.
Vertical Resolution			G	-	N/A
			B	-	
			T	-	
Temporal Resolution	d		G	5	Reasonable for climate change studies. Consistent with possibilities offered by satellite technologies (Sentinel-2 constellation can provide in the best-case images every 5 days). Will allow detecting LWE changes linked to extreme events.
			B		
			T	30	For long term evolution of lake extent changes monthly basis is still acceptable and usable. Useful to partition surface energy fluxes.
Timeliness	d		G	5	To be consistent with temporal resolution and possibilities offered by satellite technologies (Sentinel-2 constellation can provide in the best-case images every 5 days).
			B		
			T	365	Climate scale
Required Measurement Uncertainty (2-sigma)	%		G	5	For LWE, the uncertainty relatively to the total surface makes sense.
			B		
			T		
Stability	% /decade		G	5	
			B		
			T		
Standards and References	Algorithm Theoretical Basis Document (ATBD) of LWE (Lake Water Extent) calculation under ESA's CCI (Climate change Initiative) program. Mason I.M., Guzkowska M.A.J., Rapley C.G., and Street-Perrot F.A., (1994). The response of lake levels and areas to climate change, *Climate Change* 27, 161-197.				

Table 3. Lake Surface Water Temperature (LSWT) ECV product requirements.

Name	Lake Surface Water Temperature (LSWT)				
Definition	Temperature of the lake surface.				
Unit	°C				
Note					
Requirements					
Item needed	Unit	Metric	[1]	Value	Notes
Horizontal Resolution	km		G	0.1	
			B	1	
			T	2	Using satellite technics
Vertical Resolution			G	-	N/A
			B	-	
			T	-	
Temporal Resolution	h		G	3	To capture diurnal cycles
			B	24	Daily
			T	240	Currently achievable with satellite observations. Annual summary in the form of yearbook can also provide useful long-timeseries.
Timeliness	D		G	1	
			B	30	
			T	365	For yearbooks
Required Measurement Uncertainty (2-sigma)	°C		G	0.1	
			B	0.3	
			T	0.6	
Stability	°C / decade		G	0.1	
			B		
			T	0.25	
Standards and References	Technical Regulations, volume III, Hydrology, 2006 edition, WMO-No.49.				

Table 4. Lake Ice Cover (LIC) ECV product requirements.

Name	**Lake Ice Cover (LIC)**				
Definition	Area of lake covered by ice.				
Unit	km^2				
Note	Based on lake-wide satellite observations. In situ observations of ice cover can be temporally and spatially consistent, and therefore be useful for climate monitoring, but capture variations and trends in ice cover that are spatially limited (i.e. not lake-wide but rather representative of some limited area observable from lake shore). Lake-wide ice phenology can be derived from LIC (freeze onset to complete freeze over (CFO) dates during the freeze-up period; melt onset to water clear of ice (WCI) dates during the break-up period; and ice cover duration derived from number of days between CFO and WCI dates over an ice year) (Duguay et al., 2015). For lakes that do not form a complete ice cover every year or in some years (e.g. Laurentian Great Lakes), maximum ice cover extent (timestamped with date) is also a useful climate indicator that can be derived; similarly minimum ice extent can be derived for High Arctic lakes that do not completely lose their ice cover in summer.				
	Requirements				
Item needed	**Unit**	**Metric**	[1]	**Value**	**Notes**
Horizontal Resolution	m		G	50	Smaller water bodies as well as due to increased availability of synthetic aperture radar (SAR) and optical data at resolutions ≤ 50 m (e.g. Wang et al., 2018)
			B	100	Small water bodies (lakes, ponds) can be observed
			T	1000	Medium to large sized water bodies as demonstrated through ESA Lakes_cci
Vertical Resolution			G	-	N/A
			B	-	
			T	-	
Temporal Resolution	d		G	< 1	Detection of interannual variability and decadal shifts in ice cover and for improving ice, weather forecasting and climate models.
			B	1	Allows daily observations under variable cloud cover from optical satellite data
			T	3-7	Useful for contrasting extreme ice years, numerical weather forecasting, and assessing lake models used as parameterization schemes in climate models.
Timeliness	d		G	1	In support of ice forecasting systems (e.g. NOAA's Great Lakes Coastal Forecasting System, GLCFS).
			B		
			T	365	To support annual climate reporting
Required Measurement Uncertainty (2-sigma)	%		G	1	
			B		
			T	10	
Stability	%		G	0.1	
			B		
			T	1	
Standards and References	ATBD and URD of ESA Lakes_cci Duguay, C.R., M. Bernier, Y. Gauthier, and A. Kouraev, 2015. Remote sensing of lake and river ice. In *Remote Sensing of the Cryosphere*, Edited by M. Tedesco. Wiley-Blackwell (Oxford, UK), pp. 273-306. Wang, J., C.R. Duguay, and D.A. Clausi, V. Pinard, and S.E.L. Howell, 2018. Semi-automated classification of lake ice cover using dual polarization RADARSAT-2 imagery. *Remote Sensing*, 10(11), 1727; https://doi.org/10.3390/rs10111727.				

Table 5. Lake Ice Thickness (LIT) ECV product requirements.

Name	**Lake Ice Thickness (LIT)**				
Definition	Thickness of ice on a lake.				
Unit	cm				
Note	LIT measurements are largely based on in situ observational networks. Satellite-based retrieval algorithms are under development (research stage), not operational yet. On-ice snow depth measurements are also useful for both climate monitoring as well as for assessing and improving lake models.				
Requirements					
Item needed	**Unit**	**Metric**	[1]	**Value**	**Notes**
Horizontal Resolution	m		G	50	From synthetic aperture radar (SAR)
			B	1000	
			T	10000	From radar altimetry and passive microwave data (Kang et al., 2014)
Vertical Resolution			G	-	N/A
			B	-	
			T	-	
Temporal Resolution	d		G	1	From satellite observations
			B	30	
			T	365	Annual summary of in situ measurements from yearbooks
Timeliness	d		G	1	Using satellite telecommunication systems for in situ measurements; also daily from satellites for numerical models such as NOAA's Great Lakes Coastal Forecasting System (GLCFS)
			B	30	
			T	365	To support annual climate reporting
Required Measurement Uncertainty (2-sigma)	cm		G	1	Achievable with in situ measurements
			B	10	Achievable from satellite measurements
			T	15	
Stability	cm		G	1	
			B		
			T	10	
Standards and References	National standards. Kang, K.-K., C. R. Duguay, J. Lemmetyinen, and Y. Gel, 2014. Estimation of ice thickness on large northern lakes from AMSR-E brightness temperature measurements. *Remote Sensing of Environment*, 150: 1-19, http://dx.doi.org/10.1016/j.rse.2014.04.016.				

Table 6. Lake Water-Leaving Reflectance (LWLR) ECV product requirements.

Name	Lake Water Leaving Reflectance				
Definition	Water-leaving reflectance in discrete wavebands of electromagnetic radiation from near-UV through visible to near infrared and up to shortwave infrared, fully normalized for viewing and solar incident angles.				
Unit	dimensionless				
Note					
Requirements					
Item needed	**Unit**	**Metric**	[1]	**Value**	**Notes**
Horizontal Resolution	m		G	10	Small rivers and water bodies can be observed
			B	100	Water bodies included with resolution <300m, as demonstrated through Copernicus Global Land Service
			T	1000	Medium to large sized water bodies (up to 50% of global inland water surface area), as demonstrated through ESA Lakes_cci
Vertical Resolution			G	-	N/A
			B	-	
			T	-	
Temporal Resolution	d		G	<1	At equator. Allows daily observations under variable.
			B	1	At equator. Decade-scale shifts in biological components become detectable in individual water bodies.
			T	3-30	At equator. Decade-scale shifts in biological components become detectable within global lake biomes.
Timeliness	d		G	1	Episodic events can be detected in near real-time
			B	30	Satellite observations supplied with reliable meteorological ancillary data
			T	365	Annual extension of existing data records based on measurements supplied with reliable meteorological records
Required Measurement Uncertainty (2-sigma)	%		G	10	At peak reflectance amplitude. Expected to allow derived water column properties to be estimated within 0.1 mg m^{-3} chlorophyll-a and 1 g m^{-3} suspended matter or 1 NTU. See ESA Lakes_cci URD. Impact of observation uncertainty will vary with lake type (shape of reflectance spectrum).
			B	20	At peak reflectance amplitude
			T	30	At peak reflectance amplitude. A threshold cannot be clearly defined for all optical water types and lake morphologies. A larger number of observations (large lakes) may compensate for increased per-observation uncertainty.
Stability	% /decade		G	0.1	For in situ fiducial reference observations.
			B	0.5	
			T	1	Equates to 0.0001/decade for LWLR, 0.1 mg m^{-3} per decade for chlorophyll-a and 0.1 g m^{-3} for suspended matter or turbidity.
Standards and References	ATBD and URD of ESA Lakes_cci				

Looking at GCOS requirements, the current and updated resolutions for the Lakes ECVs are summarized in Table 7.

Table 7. Lake ECVs current and updated requirements.

ECV	Item needed	Current	Updated
LWL	required measurement uncertainty (2-sigma)	3-10 cm (large lakes , 10 cm other)	5-10 cm (large lakes , 10 cm other)
	stability	1 cm/ decade	1-10 cm/decade
	horizontal resolution	100 m	100 m
	temporal resolution	daily	daily-yearly
	timeliness		daily-yearly

LWE	required measurement uncertainty (2-sigma)	changes <5% (large lakes , 10% other)	changes <5%
	stability	5% / decade	5% / decade
	horizontal resolution	20 m	10-1000 m
	temporal resolution	daily	5-30 days
	timeliness		5-365 days latency
LSWT	required measurement uncertainty (2-sigma)	1 K	0.1-0.6 K
	stability	0.1 K /DECADE	0.1-0.25% / decade
	horizontal resolution	300 m	10 m-5 km2
	temporal resolution	weekly	3 hours-10 days
	timeliness		
LIC	required measurement uncertainty (2-sigma)	10%	1-10%
	stability	1% /decade	0.1-1% /decade
	horizontal resolution	300 m	50-1000 m
	temporal resolution	daily	1-7 days
	timeliness		1-365 days
LIT	required measurement uncertainty (2-sigma)	1-2 cm	5-15 cm
	stability	NA	1-10 cm/decade
	horizontal resolution	100 m	50-1000 m
	temporal resolution	monthly	1-365 days
	timeliness		1-365 days
LWLR	required measurement uncertainty (2-sigma)	30%	10-30%
	stability	1% / decade	0.1-1% /decade
	horizontal resolution	300 m	100-1000 m
	temporal resolution	weekly	1-30 days
	timeliness		1 month - 1 year

It should be noted that the Lakes_cci production teams were consulted as part of the revision process, which has helped ensure that Target requirement levels are physically realistic and feasible with current satellite capabilities. This input into the revision process was followed by a longer open consultation period.

3.1.2 Requirements from Intergovernmental Panel on Climate Change (IPCC) WGI

IPCC Working Group I (WGI) contributed to Sixth Assessment Report (AR6) targeting the assessment of the physical science basis of climate change (based on evidence from > 14,000 scientific publications by January 2021). The WG1 Report reflects recent climate science advances based on progress and integration of multiple lines of evidence, such as in situ and remote observations, paleoclimate information, understanding of climate drivers and physical, chemical and biological processes and feedbacks, global and regional climate modelling, and advances in climate services. The full report considers the current state of the climate in the long-term context, the understanding of human influence, the state of knowledge about possible climate futures, climate information relevant for climate-related risk assessment and regional adaptation, and the physical science basis on limiting human-induced climate change.

The Report is structured in three segments: 1) the first segment focuses on large-scale climate change (Chapters 2–4); 2) the second one is dedicated to climate system components and processes that play key roles in global and regional climate (Chapters 5–9), including carbon and other biogeochemical cycles, energy, and water; 3) the third one is dedicated to the assessment of regional climate information from multidisciplinary studies at sub-continental to local scales (Chapters 10–12 and the Atlas).

An important synthesis from the Report is the projection of the change of multiple climatic impact-drivers[1] (CIDs) in all regions of the globe. All regions are projected to experience further increases in hot CIDs and decreases in cold CIDs (high confidence). Further decreases are projected in permafrost; snow, glaciers and ice sheets; and lake and Arctic sea ice (medium to high confidence). Figure 1Figure 2 reports the number of land and coastal regions where each CID is projected to increase or decrease with high confidence (dark shade) or medium confidence (light shade). The projection for the CID type titled "Lake, river and ice cover" is a high confidence in decrease for about 25 regions.

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[1] Climatic impact-drivers (CIDs) are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions.

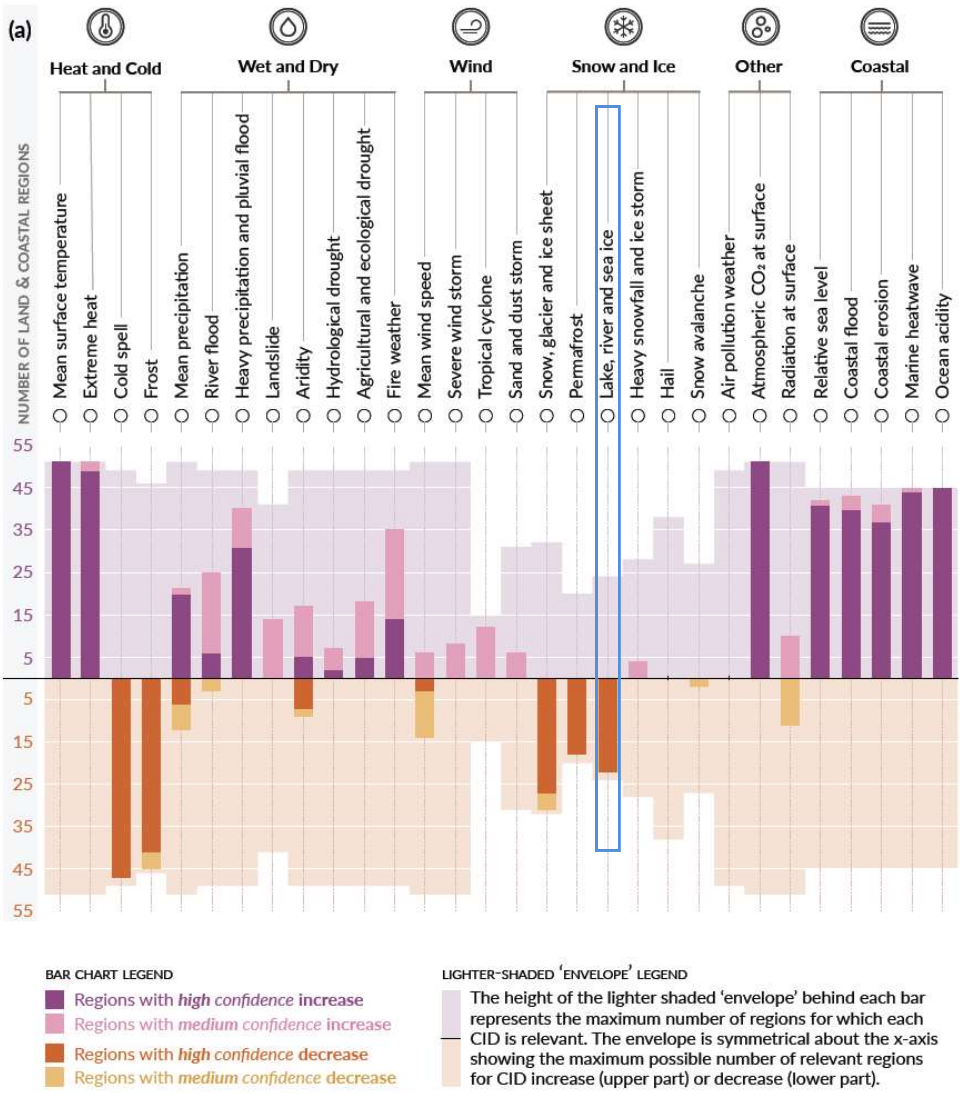

Figure 2. Synthesis of the number of AR6 WGI reference regions where climatic impact-drivers are projected to change. Panel (a) shows the 30 climatic impact-drivers (CIDs) relevant to the land and coastal regions grouped into six types: heat and cold, wet and dry, wind, snow and ice, coastal, and other. For each CID, the bar in the graph below displays the number of AR6 WGI reference regions where it is projected to change. The colours represent the direction of change and the level of confidence in the change: purple indicates an increase while brown indicates a decrease; darker and lighter shades refer to high and medium confidence, respectively. Lighter background colours represent the maximum number of regions for which each CID is broadly relevant. Le blue rectangle highlights the type "Lake, river, and sea ice". Changes refer to a 20–30-year period centred around 2050 and/or consistent with 2°C global warming compared to a similar period within 1960–2014, except for hydrological drought and agricultural and ecological drought, which is compared to 1850–1900. (Data source: modified from IPCC, 2021).

In the section on regional climate change of the technical Summary, Table TS.5 reports a summary of confidence for CID changes in each AR6 reference region. In a major part of the Asian regions and Polar terrestrial regions a high confidence decrease trend in "Lake, river and snow ice" was projected. Moreover, other significant findings including lakes are related to the Region of "Central and South America" for which glacier volume loss and permafrost thawing will likely continue in the Andes Cordillera under all climate scenarios, causing important reductions in river flow and potentially high magnitude glacial lake outburst floods. It was also reported that, in mountain areas, average warming varies with elevation, but the pattern is not globally uniform (medium confidence). Extreme precipitation is projected to increase in major mountainous regions (medium to high confidence depending on location), with potential cascading consequences of floods, landslides and lake outbursts in all scenarios (medium confidence).

Chapter 5 of the Report addresses the assessment of the global biogeochemical budgets for CO_2, CH_4, and N_2O and the assessment of C and other biogeochemical feedbacks. In this context, lakes and freshwater bodies are cited both as C burial sink and as source via outgassing, as well as sources of methane in the global CH_4 budget (see Table 5.2 in the Report). In the estimate of the latter, progress was made since AR5 in better constraining freshwater lake and river emissions and reducing double counting with wetland emissions. Nonetheless, inland water (i.e., lakes, rivers, streams, ponds, estuaries) emissions remain the largest source of uncertainty in the CH_4 budget. The main challenges are the difficulties in estimating bottom-up CH_4 emissions, due to the large spatial and temporal variation in lake and river CH_4 fluxes, uncertainties in their global area (Allen and Pavelsky, 2018), a relatively small number of observations, and varying measurement methods.

EO data might contribute to fill this spatial-temporal gap even if CH_4 estimation from EO data is also challenging as most of the studies have been conducted on methane point emissions (Guanter et al. 2021) while EO for CH_4 ebullition is more promising. Walter et al. (2008) demonstrated the potential of using synthetic aperture radar (SAR) imagery to detect methane bubbles in lake ice. Further activities linked with freeze-up at high EO resolution could be also developed to meet the IPCC needs.

Other considerations on lake extension were linked to changes on sudden local permafrost decline, due to varying causes such as melting ice in the ground reshaping Arctic landscapes, lakes growing and draining, and fires burning away insulating surface soil layers.

Chapter 8 of the Report assesses observed and projected changes in the global water cycle, the physical understanding of the complexity of its response to multiple drivers, and implications for water availability. It is well known that saline ocean water accounts for around 97% of total water availability, and that terrestrial freshwater represents less than 2% of all water on Earth, and the remainder (1-2%) is primarily made up of saline groundwater and saline lakes. 96% of freshwater are ice sheets, glaciers and snowpack, the remaining 4% is considered accessible and available for human needs and ecosystem functioning. This small fraction represents a total volume of about 835,000 km^3 of which only around 25% is stored in lakes, rivers, wetlands and soils, the other fraction in groundwater. The water cycle changes were addressed considering climate change from the perspective of its effects on water availability (including streamflow and soil moisture, snow mass and glaciers, groundwater, wetlands and lakes) rather than only precipitation. In addition, the literature indicates that increased evaporation from warmer oceans and lakes is exacerbated by the loss of surface ice in some regions. It was reported from other studies that the increase in precipitation and glacier-melt can also contribute to rising lake levels and flood hazards in regions such as the inner Tibetan Plateau, Patagonia, Peru, Alaska and Greenland. Another point is that the reduction in snow, freshwater ice, and permafrost affects terrestrial hydrology, and permafrost degradation reduces soil ice and alters the extent of thermokarst lake coverage.

The human usage and consumption of water influences the regional water cycle in a direct way by modifying and exploiting stores and flows from rivers, lakes and groundwater. The level and area of inland seas and lakes can be reduced by the widespread water extraction from rivers which reduces inflow to downstream basins. It was estimated that from 1985 to 2015, about 139000 km^2 of inland water areas have become land, while creation of dams has converted about 95000 km^2 of land to water, particularly in the Amazon and Tibetan Plateau.

Regarding runoff, streamflow and flooding, the expectation of the risk of glacier lake outburst floods (GLOFs) to increase with glacier melting in some high mountain regions is reported. Looking at other regions, heavier rainfall does not always lead to greater flooding. Some regions will experience drying in the soil, particularly in subtropical climates, which could make floods from a rainfall event less probable because the ground can potentially soak up more of the rain. However, less frequent but more intense downpours can lead to dry, hard ground that is less able to soak up heavy rainfall, resulting in more runoff into rivers and lakes. Earlier spring snowmelt combined with more rainfall (instead of snow precipitation) can trigger flood events in cold regions. In contrast, reduced winter snow cover can decrease the chance of flooding arising from the combination of rainfall and rapid snowmelt. Rapid melting of glaciers and snow in a warming climate is already increasing river flow in some regions, but as the volumes of ice diminish, flows will peak and then decline in the future. Flooding is also affected by changes in the management of the land and river systems. For example, deforestation for agriculture or to build cities can make rainwater flow more rapidly into rivers or downstream areas. On the other hand, increased extraction of water from rivers can reduce water levels and the likelihood of flooding.

The Report summarized for wetland and lakes that there is medium confidence that inland wetland extent will decrease in regions of projected precipitation decrease and evaporation increase, and high confidence that sea level rise will increase saltwater intrusion into coastal wetlands. However, there is low agreement on the influence of sea level rise on the extent of coastal wetlands. Regarding lakes, there is high confidence for temperature increases and ice decreases, based on both projections and physical expectations, and low confidence for non-homogeneous decreases in mixing, given there is currently limited evidence.

In Chapter 9, on cryosphere it was reported that the volume of proglacial lakes at retreating glaciers has increased globally by around 48% between 1990 and 2018 which can increase both subaqueous melt and calving.

In Chapter 10, "Linking Global to Regional Climate Change" a point is raised on coastal winds and lake effects. It is stated that a modelling challenge is the simulation of coastal climates and the influence of large lakes due to the complexity of coastlines, the different heat capacities of land and water, the resulting wind system, and differential evaporation.

It is stated with high confidence that climate models with sufficiently high resolution are necessary to realistically simulate lake and coastal weather including coastal low-level jets, lake and sea breezes, as well as lake effects on rainfall and snow. Another point was raised regarding the importance (medium evidence and high agreement) of including interactive lake models in Regional Climate Models (RCMs) to improve the simulation of regional temperature, particular in seasonally ice-covered areas with large fractions of lakes.

Chapter 12 on "Climate Change Information for Regional Impact and for Risk Assessment" focuses on the assessment of a few climatic impact drivers and how they are projected to evolve with climate change as to inform impact and risk assessments. Changing lake ice cover is documented in this chapter for different regions (and sub-regions) of the globe and with links to other chapters of WGI (Physical Science Basis) and WGII (Impacts, Adaptation and Vulnerability). Overall, lake ice cover duration is reported to have shortened for most lake regions in recent decades and is projected to further decrease throughout this century, reducing the seasonal viability of ice roads and recreational usage.

In the Annex 1 of the Report information on the numerical models used in the assessment was reported. In particular, "Table AII.2" reports RCMs contributing to CORDEX experiments (CMIP5-driven). In column 7 additional components such as lake, urban or river models were also reported. FLake is the model used for Lake in five models by different Institutions such as CNRM[2] (France), CLM-Community[3] (Germany), OURANOS[4] and UQAM[5] (Canada), and SMHI[6] (Sweden).

A synthesis of the requirements related to Lakes ECVs from this report is the following:

- Estimate of lake water extent is useful for CO_2 and CH_4 budget improvement and is linked to water cycle budget, as influence and is influenced by permafrost change, and is directly impacted in an

[2] Models: ALADIN63_v1, ALADIN63_v2
[3] Model: CCLM5-0-15_v1
[4] Model: CRCM5_v1
[5] Model: CRCM5_v1
[6] Models: RCA4_v1, RCA4_v1a, RCA4_v2, RCA4_v3, RCA4-SN_v1

opposite way by water abstraction or dam construction by human activities. It can also improve the estimation of the changes in the area of wetlands and artificial reservoirs.

- It has been particularly shown in Pi et al., 2022 that over the last forty years small lakes (<1km^2) account for 15% of global lake area but showed higher long-term temporal variability than large and medium-sized lakes but meanwhile contribute to 25% (for CO_2) and 37% (for CH_4) emission in the atmosphere.
- Estimates of lake storage change are useful for water storage and water cycle budget calculation, and for glacier lake volume estimation.
- Estimate of lake surface temperature can help in estimating lake evaporation, and warmer lakes can be linked to changes in surface ice in certain region, both resulting useful in water cycle budget calculation.
- Estimates of lake water level changes can track changes in precipitation and glacier-melt in particular regions and can be useful for water cycle budget calculation. It is also impacted by human activities by means of water abstraction or dam construction.
- Assessment of water lake mixing changes as suggested in Chapter 8 (Water cycle changes) of IPPC Report where is reported low confidence for non-homogeneous decreases in lake mixing due to current limited evidence.
- Lake temperature can improve RCMs simulation of regional temperature mainly in areas characterized by seasonal ice cover.

3.2 Requirements from Climate Modelling User Group (CMUG)

3.2.1 Interaction with CMUG

CMUG will work with the ECV CCI projects to provide a dedicated forum through which the Earth observation data community and the climate modelling and reanalysis community can work closely together. CMUG activities can be synthetized as follows: i) gather user requirements for ECV data sets; ii) quality assessments; iii) outreach (e.g., newsletters); iv) coordinate forums for communication (like the Climate Science Working Group – CSWG); v) publicity for the ECV datasets to the climate research and monitoring communities; vi) ECV inclusion in databases such as obs4MIPs and the Copernicus Climate Data Store.

The "Deliverable 3.1 - Quality Assessment Report" of the CMUG, which has the objective to assess the consistency and quality of CCI products across ECVs applied, included the experiment of the WP3.7 dedicated to the analysis of the Effect of Lakes on local temperatures. The experiment typology is under the label assimilation and process understanding. The aim of this study was to identify and describe the interactions and relationships between lakes, typically around large lakes, and their surrounding land areas. The Met Office group reported the potentiality of the Lakes CCI ECVs in term of filling an important data gap in climate observations together with the potential to improve the representation of lakes in climate models, particularly where in situ observations are sparse. The first intention in the experiment was to use the daily LSWT and LIC ECVs as input to the HadREM3-GA7-05 regional climate model over Europe at 12km horizontal resolution driven by ERA-.Interim and prescribed daily sea surface temperature and sea ice from Reynolds et al (2002). However, the LSWT and LIC datasets were substituted by the daily ARC3 lake data set due to the amount of missing data (likely due to cloud) currently present in the Lake ECVs. Specifically, the choice was explained in detail looking at the histograms reported in Figure 3 where the fraction of lake grid boxes (in the European RCM domain) that contain non-missing data each day in the period 1996-2011. All available (not missing) LSWT data is counted as valid. In winter when there are likely to be more days of cloud cover, there is a high proportion of days with little to no data: in DJF (JJA), ~63% (~28%) of days contain 0 - 5 % of non-missing data for LSWT. LIC tends to have fewer, but still significant gaps, in DJF(JJA), ~31 % (~25 %) of days contain 0 – 5 % non-missing data. Whilst the picture is better in the summer, for LSWT only ~0.6 % of days contain

> 80 % non-missing data. It was also highlighted that the gaps due to cloud are often spatially variable (e.g., one lake might contain data in all grid boxes containing data, but another in the domain has no data). It was concluded that at present, the LSWT and LIC could not be used as input to prescribe lake surface properties in these climate models, and would be of very limited use to validate RCM output or lake model output. The report also stated that the interaction with the Lakes ECV team helped in understanding the dataset produced and that the team suggested alternative dataset which better matched the high-frequency/completeness requirement for using lake ECVs in a regional climate model experiment.

In the summary, a suggestion was to apply a data reconstruction as was done to a previous ESA LSWT product (ARC3; MacCallum and Merchant, 2012), to become very useful. It was also reported that it can also be beneficial, if scientifically/mathematically plausible, to try to build on ARC3 by creating a spatially coherent daily time series, rather than point data. Finally, it was pointed out that spatial data would be particularly useful for larger lakes.

This user requirement (from climate modelling community) was already reported and analysed in the previous URD; a new discussion point in this version of the document is about the technical feasibility to join this need, and the trade-off between requirements and feasibility.

Following the analysis of scientific requirements expressed by the users, we summarize an updated requirement to include eight times more lakes, with efforts on gap filling and more suitable tools to extract and analyse the data product. The feasibility of meeting this requirement is limited by both computational capacities and the resolution of existing (and particularly, legacy) sensors.

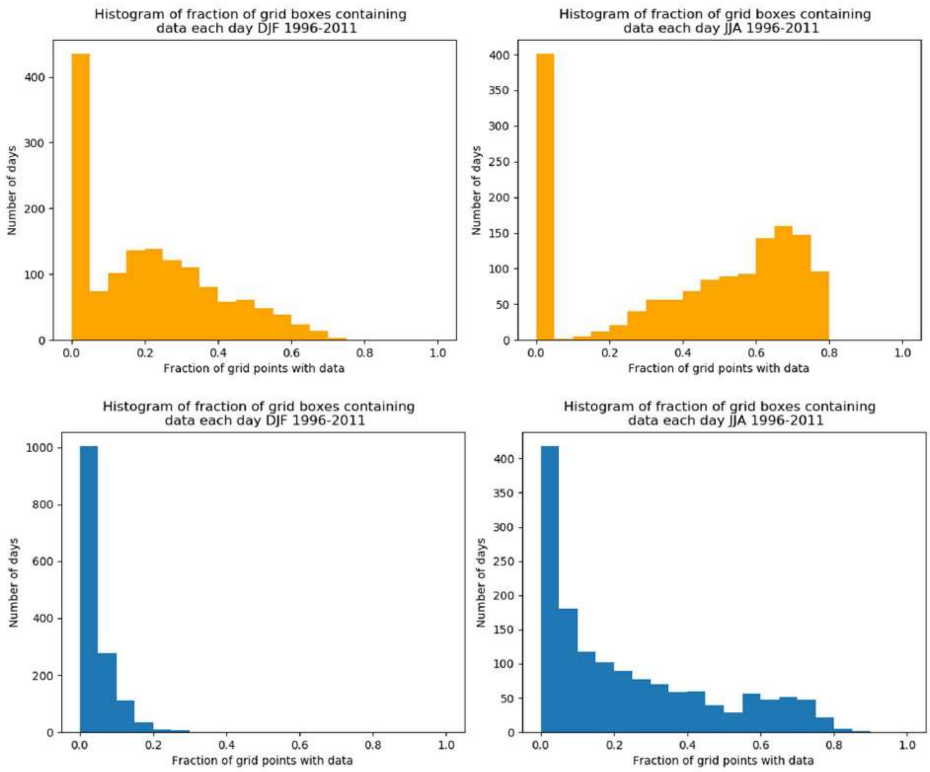

Figure 3. Histograms of the fraction of grid boxes containing data (i.e., not missing) each day in the European RCM domain for the period 1996-2011 LIC (orange) and LSWT (blue) (from Deliverable 3.1 of CMUG)

Exchange of ideas for model experiments in phase 2 is in progress. In addition to the UK Met Office, SMHI posed a series of questions and feedback on how to better exploit the Lakes dataset against their models. In particular, they are testing their global climate model EC-Earth with the *FLake* lake model. They plan to compare the modelled lake temperature and ice with Lakes ECV data. Requirements consist of monthly data, and the need for some code to extract individual lake data. Moreover, their request was to provide data on a coarser grid (i.e., 0.25 degree) due to the resolution of their global Earth model, as higher resolution is more time consuming in data extraction. A script has been provided to download data for a single lake, and we added that during the second phase, some scripts will be proposed for final users, but our current objective is not to filling gaps or provided data at different resolutions. The latter is another point that can be assessed in the trade-off between requirements and feasibility including cost.

3.2.2 2022 CMUG Integration & Climate Change Initiative Colocation

The CMUG Integration and CCI Colocation meeting was held in Frascati from 24 to 27 October 2022 (https://climate.esa.int/en/events/12th-cci-colocation-meeting/; Figure 4). The first two days were dedicated to CMUG Integration meeting where the findings from the different WPs were presented, and the Phase 2 proposal was introduced to the wider community.

Figure 4. Location of the CMUG Integration & Climate Change Initiative Colocation in ESRIN, Frascati (Italy) from 24th to 27th October 2022.

The presentation on WP3.7 on "MOHC RCM study using CCI Lakes data", repeated the finding that the global LSWT and LIC ECVs from Lakes_cci project were not currently useable in climate model simulations due to gaps (observation intermittence against daily data request), and suggested a reconstruction such as applied to the ARC3 lake data set. Subsequently, seven themes on machine learning, vegetation/hydromet, land surface, ocean biogeochemistry, cloud and aerosol, snow dynamics, and high latitude/ice sheets were presented and subject of breakout discussion groups. The Land cover group made a summary of the resolution of the ECV products related to Land (land cover, land surface temperature and soil moisture, together with the recent LAI and FAPAR). For example, Land Cover V1.1.1 product is at a resolution of 300 m (C3S) and is coupled to a 300 m, 14 Plant Functional Types (PFTs) products (300 m) which includes 4 forest types, 4 shrub types, natural herbaceous, croplands (LC distinction between irrigated/rainfed), C3/C4 from LSCE, wetlands, urban, bare soil, and water, snow and ice. This latter category comprises lakes and can be interesting a comparison with our LWE product.

The second part of the meeting was dedicated to the CCI Colocation. The sessions included: i) Feedback from the Science Leads on the Current Activities, ii) CCI Knowledge exchange, iii) Evolving Requirements from GCOS, and iv) Evolving Requirements from IPCC.

The main feedback from the Science Leads relevant to the Lakes CCI was related to the need to foster information exchange between ECVs and subgroups discussions led by Science Leaders under the guidance of ESA, in particular on gap analysis for X-ECVs, cross-consistent CCI products, joint scientific exploitation of CCI products (e.g., publications), and prioritised requests for data reprocessing, new mission products, etc. To respond to these requirements and to strengthen interactions with ESA, it was proposed to create a Science Leader Coordination Group (ca. four people; 2-year terms) from different perspectives. Under CLIMATE SPACE there is the need of a continuity of R&D at ECV level, for methodological development of algorithms for existing products (including new missions, homogenisation of products), to develop new variables within existing ECVs as requested by GCOS, and to start R&D on X-ECVs and on Tipping Points involving CCI teams. Regarding the provision of CCI related ECV products at various portals (e.g., ODP, C3S/CDS) there is the need of a cross catalogue search to increase the use of products capability (and ideally online processing on request), and CCI+ projects should get the link to users and get access to user feedback, independently on the portal where CCI+ products are distributed. To solve the duplication of products within CCI+ and other data portals a better coordination is required.

One Science Lead for each domain (Land, Ocean, Cryosphere, Atmosphere) presented the main objectives, R&D topics, and use cases for each ECVs included in each domain. For Lakes ECV the new contents of the Phase 2 project were presented.

In the knowledge exchange session, we've highlighted the priorities for Climate for Space Graphic to show i) all ECVs, ii) significant data updates, and iii) additional parameters or new visualisation styles. At present only LSWT is reported in the list of CCI ECV for climate for space.

Interoperability between CCI ECVs and Climate services such as C3S is a clear requirement to support ECV products dissemination and knowledge exchange.

In the session on GCOS requirements the new development from the ocean, atmospheric and terrestrial observation panels were presented (see the previous section 3.1.1). From the TOCP Panel, one of the highlights form the new GCOS-IP is the evolving requirements for more rapid data delivery (incl. near real time) to make ECV records more useful and actionable addressing climate change mitigation and adaptation. From the presentation of the OOCP Panel was highlighted that currently there is not a single access point to be able to compare satellite to in-situ data and the risk of redundancy in developing tools. To sustain monitoring and policy needs, in the presentation of the FAO it was suggested the need for a better integration of measurable field, airborne and space borne remote sensing parameters with practical (monitoring) solution and policy implementation. Moreover, one of the take home messages from FAO is that EO with long data records and data over remote places can help in validation of climate and other models, in monitoring and early warning, and in process understanding. The importance of free and open EO data was also reaffirmed.

Then starting from the recent IPCC AR6 the discussion was based on the questions on how to support climate modelling with EO data, which is the role of EO data in tackling climate change and finally, the future plans towards AR7 were presented. From the CMUG, the main bullet points on how EO data can support Climate Modelling are the following: i) assessing improvements and errors in model ensembles and related technical infrastructure; ii) evaluating the quality of observations for constraining climate models and processes studies; iii) Detailed assessment of drivers of model biases, implications for and demonstration of model improvements; iv) exploring anthropogenic drivers of climate changes including sensitivity experiments and attribution of climate events and changes. In this talk, it was reported that the part of the CCI data were used in the recently released IPCC AR6 report3, and therefore the increase of the number of CCI datasets available through ESMValTool can provide additional lines of evidence for future IPCC and other such reports advising on policy changes. The potentiality of the interaction with Obs4MIPs (Observations for Model Intercomparison Projects) which is a climate model community initiative to encourage widespread uptake of satellite observations for climate model verification and development, can be a way to extend the use of CCI dataset. Actually, aerosol, GHG, SST are examples of ECV included in Obs4MIPs. Other CCI dataset (SST, Sea Level, Sea Ice, Ocean Colour) were used for reanalysis with in situ measurements of temperature and salinity. Moreover, in another case study, Soil Moisture ECV demonstrated the improvement in CMIP6 atmosphere-land-surface model.

Finally, four breakout sessions, ocean, land, atmosphere, cryosphere, discussed both on implementation of GCOS evolving requirements and on how to address knowledge gaps in preparation of AR7.

The summary for the Land breakout is reported below, focussed on four questions:

1) What are the major challenges posed by the evolution in your respective domain in the GCOS 2021 plan (by comparison to 2016) in terms of threshold, breakthrough, goals? How would you address these challenges in future projects and/or CLIMATE-SPACE. Suggestions from Lake Science Leads are reported in Table 8.
2) GCOS AND Global Stock Take (GST): How could you contribute to the six GCOS implementation themes?
    a. How can we ensure continuation of consistent time-series of ECVs and reanalysis?
    b. How can data be made more available and of greater utility?
    c. What are the reprocessing requirements?
    d. How are we currently managing data and what improvements can be made?
    e. Should we engage more with countries and what mechanisms should be put in place?
    f. What are the emerging needs?

    Suggestions from Lake Science Leads are reported in Table 9.

    Where/what are the data gaps? ECVs, EO data, in situ data. Comments from Lake Science Leads are reported in Table 10.

3) How do you see the role of your ECV with others? as inputs to high to low resolution land cover mapping; as discerning the impacts of change; as identifying the pressures leading to change; correcting EO data to better support retrieval of ECVs. Suggestions from Lake ECVs Science Leads included in Land domain are reported in Table 11.

In addition, other comments are reported in Table 12.

Table 8 Reply of Lakes cci to the first question of the Land Breakout.

What are the major challenges posed by the evolution in your respective domain in the GCOS 2021 plan (by comparison to 2016) in terms of:	**LAKES**
Threshold? *The minimum requirement to be met to ensure that data are useful*	Thresholds are (broadly) adopted as suggested by us, so they are attainable with current sensors. Legacy sensors might not always meet requirements.
Breakthrough? *An intermediate level between threshold and goal which, if achieved, would result in a significant improvement for the targeted application. The breakthrough value may also indicate the level at which specified uses within climate monitoring become possible. It may be appropriate to have different breakthrough values for different uses.*	Further developments required, e.g. ensuring data quality from high-resolution sensors. Long-term records not consistently attainable across the tECVs due to lack of high resolution legacy sensors. Some tECVs (LWE, LWL) more likely to succeed than others (LWST, LIC, LWLR).
Goal? *An ideal requirement above which further improvements are not necessary.*	Some variables attainable regionally through integration of satellite, in situ data e.g. through model reanalysis.

How would you address these challenges in future projects and/or CLIMATE-SPACE?	High resolution methods (LWLR, LWST, LIC) need to be developed and globally validated. Hyperspectral sensors may also be considered. Improved access to in situ validation data is key to reduce uncertainties, ensure stability.

Table 9 Reply of Lakes cci to the second question of the Land Breakout.

GCOS AND GST: How could you contribute to the six GCOS implementation themes?	**LAKES**
How can we ensure continuation of consistent time-series of ECVs and reanalysis?	Sustainability is a key issue, **(re-)processing effort is large for LWE, LWLR**.
How can data be made more available and of greater utility	Suggest to focus higher-resolution needs on key areas of change/risk. We encourage data access and visualisation tools that work across the CCI. API to get data on specific lakes/region Harmonized metadata with other ECVs
What are the reprocessing requirements?	Eventually (soon?) will need to **move to larger facilities** (not all tECVs) where all input data are located
How are we currently managing data and what improvements can be made?	Gap-filled data are desired by users, not in scope of current activities. LWE is provided as areal extent (one value/day per lake) whilst spatial extent (shoreline dynamics) would be preferable.
Should we engage more with countries and what mechanisms should be put in place?	Yes, to get **calibration/validation data** and promote climate data produced in CCI and get their feedback.
What are the emerging needs?	**High resolution data on climate change hotspots** Lake storage changes are important to consider (dedicated option in Lakes_cci project)

Table 10 Reply of Lakes cci to the third question of the Land Breakout.

Where/what are the data gaps?	**LAKES**
ECVs	Lake vegetation (submerged, floating) Carbon pools
EO Data	**Access to very high resolution images to validate low resolution data** (water surface for instance, stereo image for DEM) is needed, particularly for LWE. A high resolution optical 'water' mission, for optically complex waters (including small water bodies and rivers), is non-existent. High-resolution thermal imaging needs to be consistently validated.
In situ Data	**MAJOR GAPS PLEASE HELP**

	(expand coordinating networks such as GTN-H to include all lake variables, or create new tiered networks. National inland water monitoring programmes are predominantly shore-based so have limited complementary value. Lake ice thickness, lake extent surveys and in situ radiometry are very rare) There is no consistent funding mechanism to collect nor collate the required in situ datasets, other than what is already in Hydrolare, GTN-H

Table 11 Reply of Land ECVs to the fourth question of the Land Breakout.

How do you see the role of your ECV (with others)?	As inputs to high to low resolution land cover mapping	As discerning the impacts of change	As identifying the pressures leading to change	Correcting EO data to better support retrieval of ECVs
LAKES	Land cover category (extent). Land degradation and its impact on water quality.	Inundation frequency, drought frequency, link between water quality and quantity. Impact on total water storage, human and animal health (incl. disease), community connectivity (e.g. Arctic over-ice transport).	Changes in lake level, lake pollution, algal blooms, links to human and animal health. Increase in temperature, & snow / glaciers melt.	Ensure consistency between different ECVs (land, cover, soil moisture, permafrost and other cryosphere ECVs)

Table 12 Other comments from Lakes cci as requested by Land Breakout

Other general comments	LAKES
Fiducial Reference Measurement (FRM) network requirements	To reach Target requirements, in situ reference need not always be up to FRM standards, data volume is crucial. To reach B/G requirements, FRM standardisation is required and requires strategic site planning.
Product continuity is key (not only space mission continuity). Changing retrieval algorithms and discontinuing products too often should be avoided because users would then need to recheck everything in their work environment. Discontinuing historical product versions should be avoided unless for very good reasons. Maintaining old and new products for a while (at least 1 year) is needed. Overlap between product versions is needed.	Water cycle budget and freshwater and sediment / pollutant fluxes to ocean to be considered, ideally combining observation and hydrological modelling. ⇒ suggested for ECV River Discharge

Finally, another key point for the immediate future raised at the Colocation meeting was the development of Cross-ECV studies at CCI level with current and proposed ECVs for climate mitigation and adaptation as requested by international panels.

The meeting highlights a general need for wider and strengthened interaction between the different parts of CCI, such as between the different ECV teams, between ECV teams and CMUG to try for example to design the experiment together, along CCI teams, ESA, and GCOS/IPCC to better address their requirements.

4 Requirements from the lake research community

4.1 Third User Survey

The third questionnaire (https://climate.esa.int/en/projects/lakes/news-and-events/news/third-users-survey/) is addressed to climate scientists, lake scientists and the wider scientific and expert user community interested in observing lakes. This survey forms the third user consultation of the project, collecting feedback and requirements to align the project with user needs in the Phase 2 of the project (**Erreur ! Source du renvoi introuvable.**). It is focused on the use of the dataset produced in the Phase I.

A synthesis of the statistics of the download of the Lakes_cci dataset is supplied by the CEDA catalogue website and is reported in Figure 6.

Until the 10 December 2022, 33 answers were received, and it is important to consider that the latest version of the dataset expanded to 2024 lakes was available at the beginning of July 2022. In the following paragraph 4.2 we also report the dissemination activities.

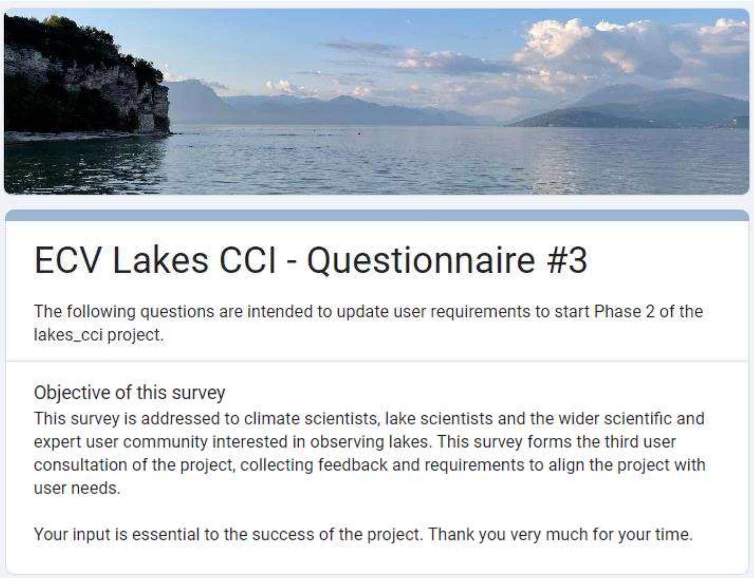

Figure 5. Webpage of the third questionnaire on the use of the ECV Lakes.

Method	Users	Datasets	Number of accesses	Size	Activity days
anon-ftp2.ceda.ac.uk	2	1	21.005	1.03 TB	13
cci-thredds-download	4	1	116	10.25 GB	4
cci-thredds-subset	10	1	1.268.208	251.62 GB	31
dap-thredds-download	84	1	34.010	1.67 TB	111
ftp3.ceda.ac.uk	6	1	39.614	1.76 TB	20
Totals	**99**	**1**	**1.362.953**	**4.72 TB**	**179**

Figure 6. Method, users, number of accesses, size and activity days related to the Lakes_cci dataset.

The questions have the scope to understand the background of the users, if the users exploited the Lakes_cci dataset, and if some issues were encountered and what improvement are suggested. The questions are the following:

1. What are your disciplines of interest?
2. How did you find out about the Lakes_cci products?
3. Did you use any Lakes_cci products? If so, for which purpose(s)?
4. Which thematic variable have you used to date?
5. Which version of Lakes_cci products have you used?
6. Which geographic area and temporal range did you investigate?
7. If you compared the products with other datasets how was the relationship?
8. Did you use any post-processing of the data? If yes, specify all that applied.
9. If you encountered any issues with data access, what were they?
10. What improvements would you recommend?
11. Is the documentation on data products sufficient for your purposes?
12. Do you have any suggestion to improve data products documentation? (e.g., FAQ on website, tutorial/video)
13. Do you need other thematic variables to be developed?
14. Did you use other CCI ECVs? If you used any other CCI products, how did you use them and for what purpose?

4.1.1 Results

In this section the answers of 33 users to the third questionnaire are reported.

1. What are your disciplines of interest?

The main disciplines of interest based on 32 responses are limnology, hydrology, ecology, followed by climatology, biogeochemistry, and biology (Figure 7).

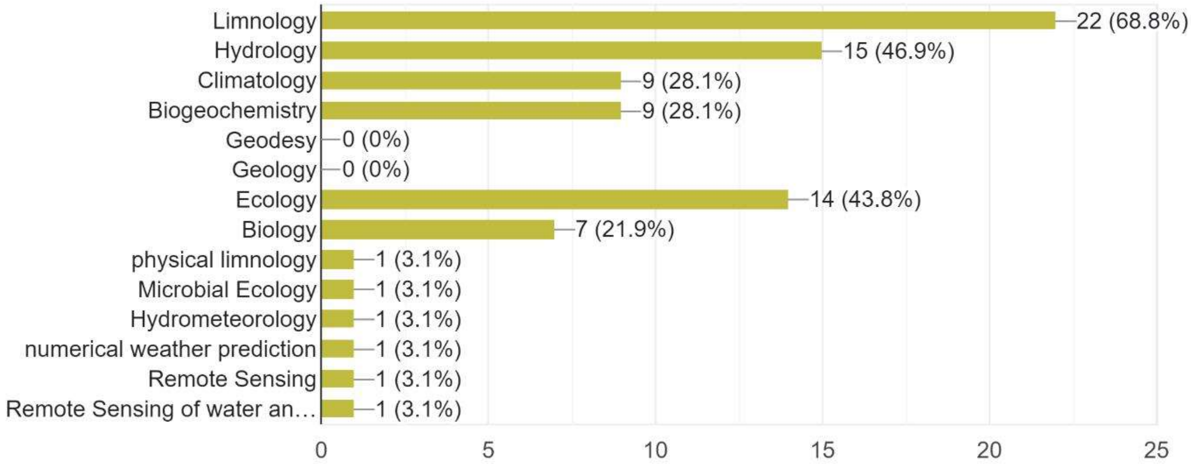

Figure 7. Histogram of answers to question 1.

2. How did you find out about the Lakes_cci products?

Conference/meeting and scientific paper are the main sources where the users found the Lakes ECV products, the rest mainly by social media and personal contact (Figure 8).

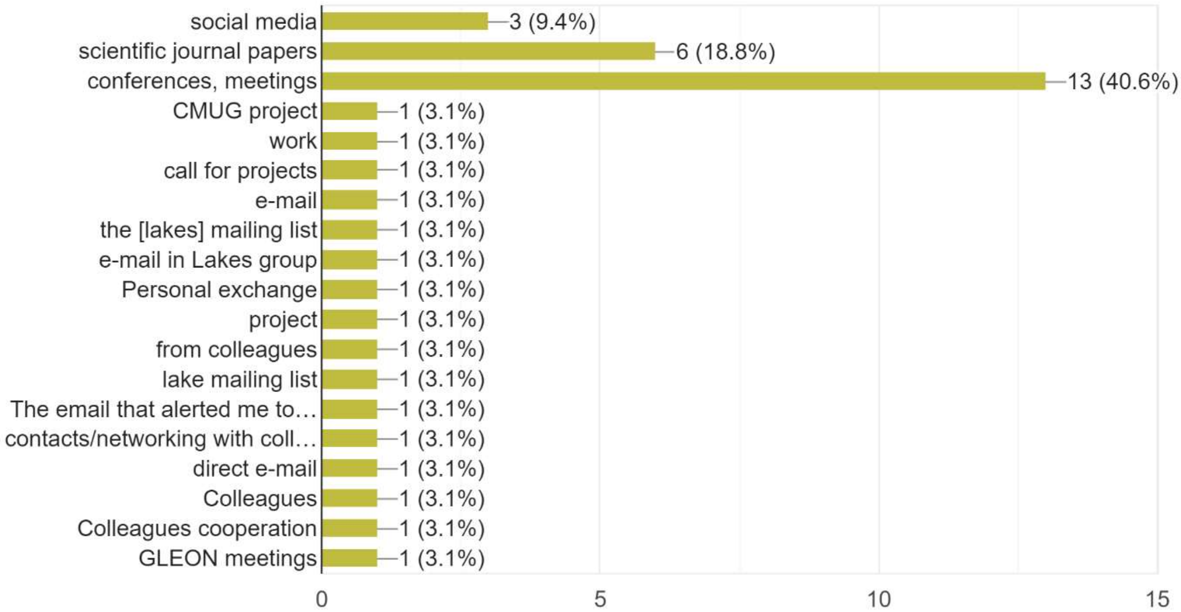

Figure 8. Histogram of answers to question 2.

3. Did you use any Lakes_cci products? If so, for which purpose(s)?

The Lakes_cci products have been used from a minority of survey responders, and mainly for understanding causes of environmental changes, climate modelling, and the assessment of trends and geostatistics followed by other model related applications (Figure 9).

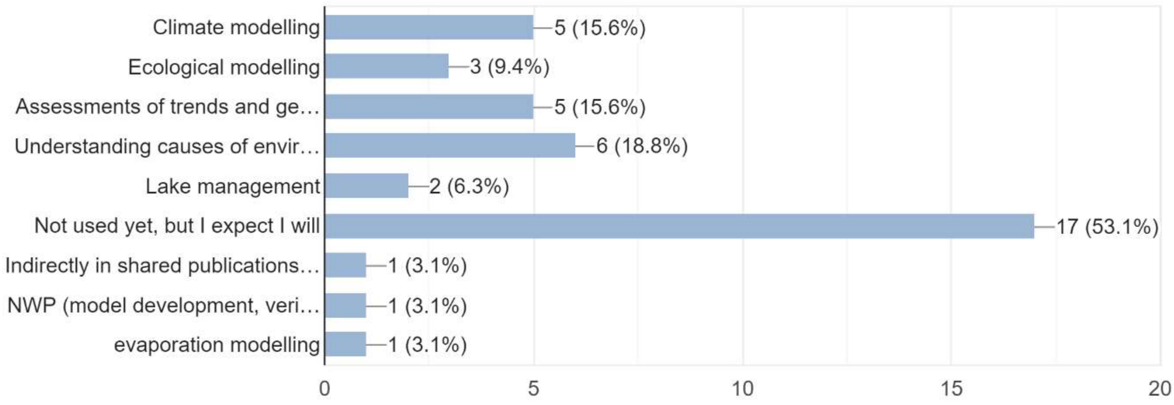

Figure 9. Histogram of answers to question 3.

4. Which thematic variable have you used to date?

All the thematic variables were used. The variable used with more frequency is LSWT followed by ice cover and LWLR (21 responses; Figure 10).

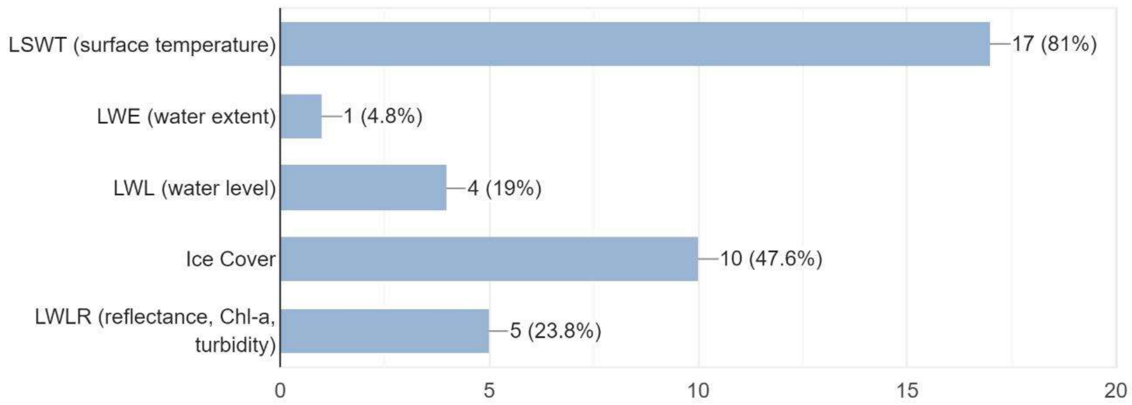

Figure 10. Histogram of answers to question 4.

5. Which version of Lakes_cci products have you used?

Based on 18 responses, the version 1 of the dataset was mainly used, followed by version 2 (Figure 11).

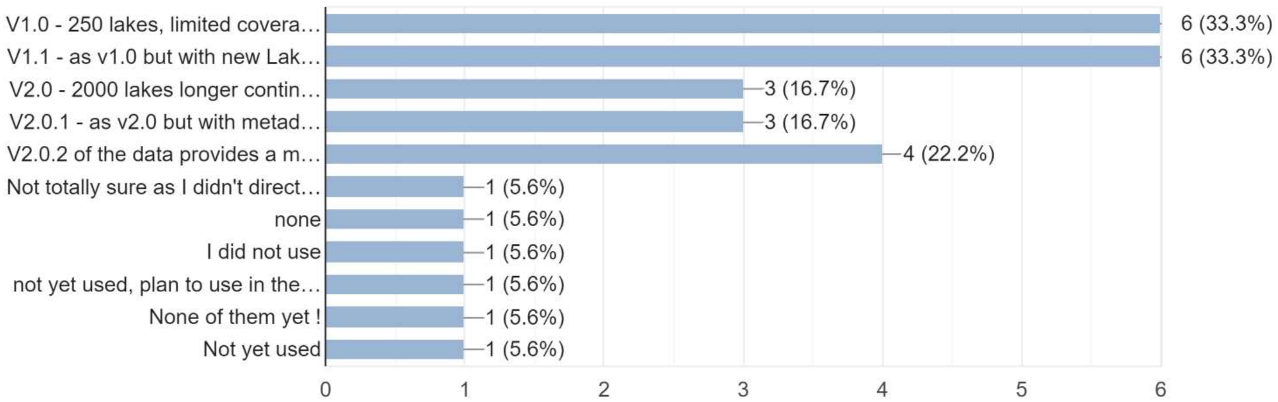

Figure 11. Histogram of answers to question 5.

6. Which geographic area and temporal range did you investigate?

The list of the 16 responses is presented below:

- Europe, all the available period of the dataset
- Northern Europe
- Global and 2000-2020
- Alpine region and global dataset
- Central Europe
- Tropical, seasonal and diurnal scales
- Alpine Region for more than 30 years
- Global, continuously updated data
- 1950-present, Mediterranean South America
- All available lakes, from 2000 to 2020 because of better coverage.
- Garda Lake from 1995 to 2019
- Rappbode Reservoir (70 km length, 200 m width)
- Europe
- Global, entire time series
- Northern Italy, full time series
- Germany and Armenia

7. If you compared the products with other datasets how was the relationship?

About 43% of the responders was not sure. For the rest another 43% declared that the relationship was good, 10% that depended on lake type, and the rest 4% (1 response) that the relationship was fair (21 responses).

8. Did you use any post-processing of the data?

55% of the users answered yes and the rest vice versa (total of 22 responses).

9. If yes, specify all that applied.

The post processing applied are gap filling, outlier removal, and smoothing. The supplied uncertainty data was also used for example to filter results (Figure 12).

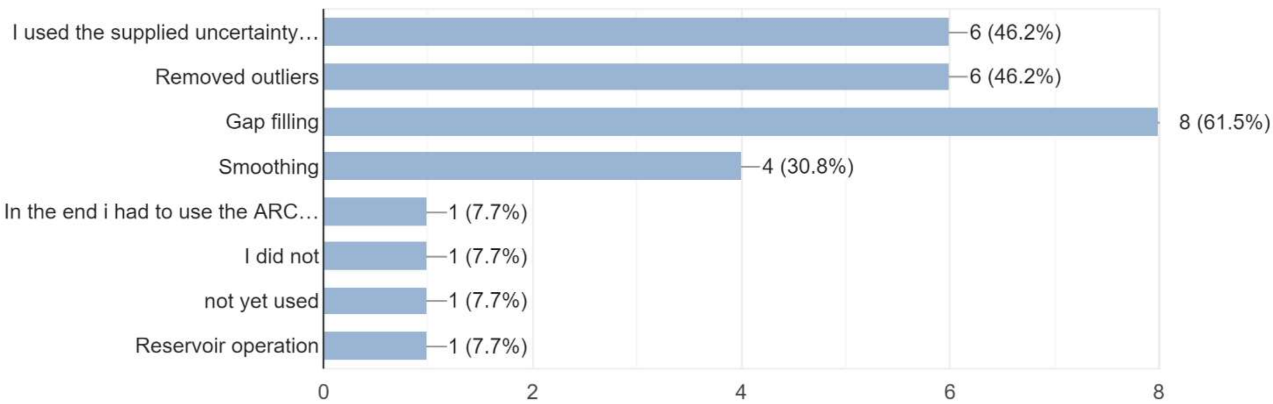

Figure 12. Histogram of answers to question 9.

10. If you encountered any issues with data access, what were they?

The majority of the responses were “none”, other answers reported parameters, and format (both and “global product, file size” and “variable, netCDF”) (19 answers; Figure 13).

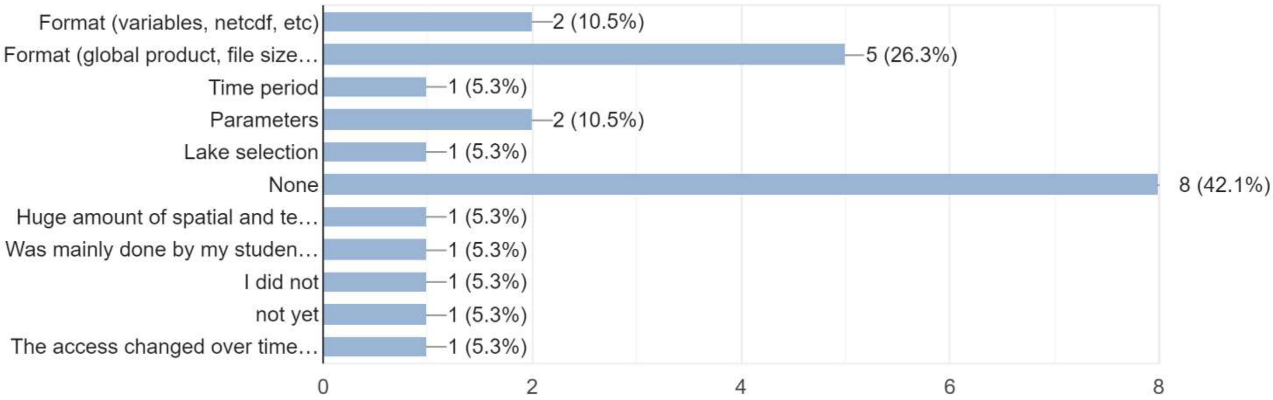

Figure 13. Histogram of answers to question 10.

11. Please elaborate on any issues encountered.

The list of issues is the following:

- In version 2.0.2. not all variables are included in the netCDF files. Files must be homogeneous even when some variables are missing (e.g. by putting empty variables in the netCDF), so that automatic codes can work properly to download the data via the URL.
- The gaps in the data made the data unusable for the climate modelling context i.e. comparing to model output or using them as an ancillary for re-analysis runs.
- Extreme climate events.
- It is always beneficial to increase the available data in spatial and temporal extent.

12. What improvements would you recommend?

The recommended improvements are reported in Figure 14 (21 responses). The first one is the increase of the number of lakes (71%), followed by increased frequency (48%), and with the same percentage gap filling and increased data quality (33%).

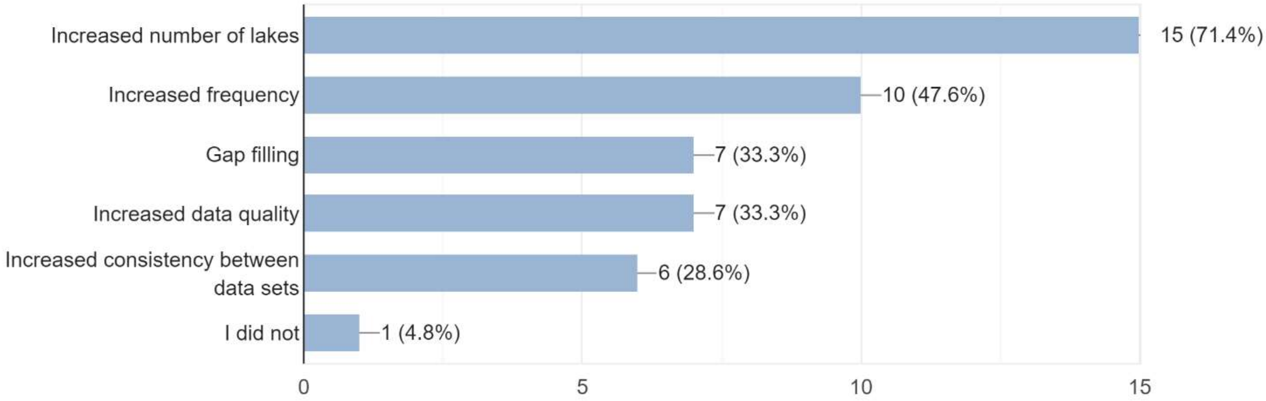

Figure 14. Histogram of answers to question 12.

13. Please, detail the needed improvements

The 10 responses are listed below:

1. For the specific purpose of using these datasets to prescribe lake surface temperature and ice, gap filling would be needed, since models require regular, high frequency updates of these variables.
2. The technique applied by Woolway for ARC3 for gap filling would greatly increase the usability of the data for climate modelling work.
3. Spatial resolution should also be increased by integrating data from other sensors with finer spatial detail. This will lead to the increase of number of lakes with smaller water bodies as well as to the increase of frequency of data.
4. I prefer as many data from the greatest number of lakes.
5. Hydrological data are not often enough to define trend, also they are not continuous and not for all lake they are available.
6. An increase in the temporal frequency of the data would be very useful detailed global coverage is very desirable.
7. Definition of lakes. There is an uncertainty on what are the limits between lakes, large river or inundated areas. They are all open water but some are stagnant, some are running a finally some are seasonal. For space observations this makes no difference but in our effort of trying to simulate these water bodies they are very different from their behaviour and response to perturbations.
8. Providing a gap-filled version of the dataset would make the dataset more attractive to users.
9. Explore an increased number of lakes, also with smaller size.
10. In particular increased number of lakes and spatial coverage is useful. Gap filling would be very useful for some data sets.

14. Is the documentation on data products sufficient for your purposes?

Based on 20 responses the users were somewhat satisfied (50%), extremely satisfied (15%), neither satisfied nor unsatisfied (20%), and somewhat unsatisfied (15%) (Figure 15).

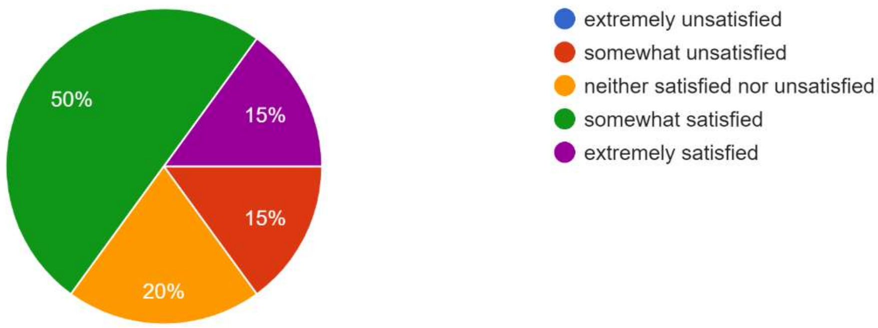

Figure 15. Pie chart of the answers to question 14.

15. If you answered 'extremely or somewhat unsatisfied', could you please indicate the main issue/s?

Of four responses, three were not available and two commented as follows: i) as above: what is a lake? This requires a proper definition so that it can be differentiated from other water bodies. What about natural and man-made lakes?; ii) when I accessed the data which was some time ago, it was not clear to me whether the raster represented median, mean, over which time period.

16. Do you have any suggestion to improve data products documentation? (e.g., FAQ on website, tutorial/video)

The 8 responses are listed below:

- Better explanation of uncertainty levels, especially for ice.
- I know some people downloaded the entire dataset (very heavy and time-consuming approach) for extracting single lakes. It would be useful if some codes (R, python, MATLAB) are made available e.g. on a GitHub repository or official channels to download the lakes quickly.
- Tutorial/video.
- Videos and tutorials are always helpful.
- Yes, clarify what lakes are.
- The general documentation is fine. I would only better clarify the changes when a .0.1 or .0.2 version is released.
- FAQ.
- Good tutorials and videos are always use to provide infos in a rapid and understandable way.

17. Do you need other thematic variables to be developed? (e.g. coefficient of extinction [Kd], Coloured Dissolved Organic Matter [CDOM], Forel-Ule colour index, Ice thickness, Lake volume change?)

The 13 responses are reported in the following:

- Kd or Secchi depth maps would be very useful, as well as Lake volume change.
- Ice thickness, snow cover and Kd.
- Yes. CDOM would be very helpful.
- coefficient of extinction [Kd], ice thickness.
- All of the above.

- CDOM, Ice thickness, Lake volume change, possible other parameters on changes in lake morphology and biochemistry, e.g. ash and microplastics concentrations, greenhouse gases, especially methane.
- Information on water uses, withdrawals.
- Extinction coefficient and ice thickness (possibly snow thickness) would be very useful for modelling purposes. Then lake volume change is also of interest for hydrology and the water cycle.
- Kd.
- Yes, that would be very interesting and it would probably enlarge the scope of use of the dataset.
- Dominant wavelength from chromaticity.
- CDOM would be very useful for our purposes.
- Coefficient of extinction [Kd], Ice thickness.

18. Did you use other CCI ECVs? If you used any other CCI products, how did you use them and for what purpose?

The other CCI ECVs mainly used were related to Land domain such as land cover (50%), LST (30%), HRLC (30%), followed by SM, Water vapour, GHGs, and SST (10 responses; Figure 16).

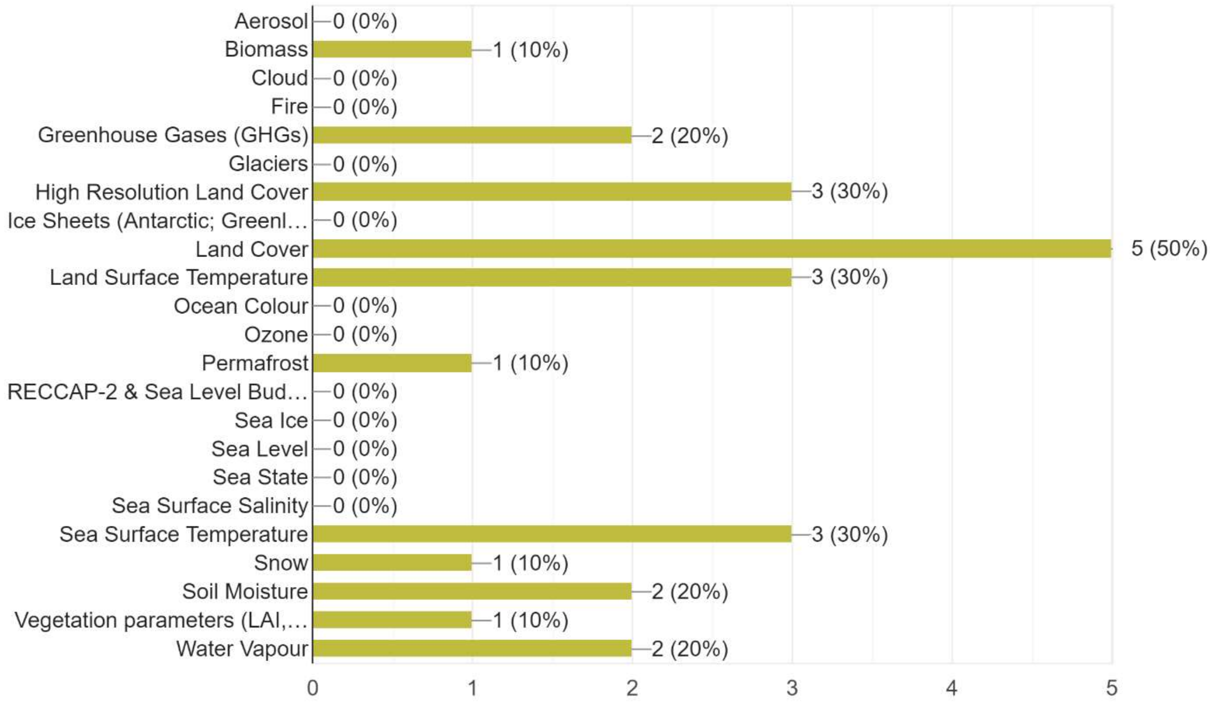

Figure 16. Histogram of answers to question 18.

19. If you used any other CCI products, how did you use them and for what purpose?

The 6 responses are reported below:

- Climate model re-analysis comparison
- I use CCI land cover as high-res input data for land surface models.
- To evaluate hydrological balance and hydro-morphological impacts on lake.
- ESA-CCI LC product is combined with other datasets (land sea mask, lake mask…) to derive the classification we are using for land surface modeling.
- Model development and validation.

- Optical properties for some ground truthing, in particular pigment data.

4.1.2 Summary of the user survey

From this third questionnaire, we obtained some confirmation about the main scientific disciplines interested in Lakes_cci variables, which are limnology, hydrology, ecology, followed by climatology, biogeochemistry, and biology. Among the lake variables the major interest is towards LSWT, LIC and LWLR. Version 2 of the dataset is starting to be exploited in addition to version1. Data will be mainly used for the assessment of trends and geostatistics, to understand causes of environmental change and for climate modelling. At the spatial and temporal level, studies have been done on a global or regional scale for long time series. The post processing applied to the dataset was mainly gap filling followed by outlier removal. A few issues reported on data access were related to formatting. Other recommended improvements were the increase of the number of lakes (71%), but we have to remind the majority of users used the first version which covered 250 lakes, followed by increased frequency and data quality, and gap filling. Other thematic variables to be developed can be CDOM and Kd. In general, the documentation on data products is sufficient, some needs are for script/code available in repository such as GitHub (and we already made available a couple of scripts to download data for a single lake, by boundaries or by lake_id), and tutorial/video and FAQ on Lake_cci website. Finally, the other CCI ECVs used with Lakes ECVs are related to Land compartment (LC, HRLC, LST, GHG).

4.2 Dissemination activities

The partnership widely disseminated the activity of the Lakes_cci project through:

- attendance to meeting and conferences (*e.g.*, EGU, CCI Colocation, ASLO, etc.),
- promotion of data availability to appropriate community (*e.g.*, AquaWatch) and
- presentation of the project to partner network (*e.g.*, GEO AquaWatch, GLEON)

The dissemination of our dataset and of the link to the survey was done across GeoAquawatch website (Figure 17), and GEWEX International Linked in web page (https://www.linkedin.com/posts/gewex-international-82b63073_lakes-activity-6986451628014911488-tyGR?utm_source=share&utm_medium=member_desktop). In addition, one of the Science Lead contributed to the GLORIA global lakes dataset across the activity of validation of radiometric data from lakes.

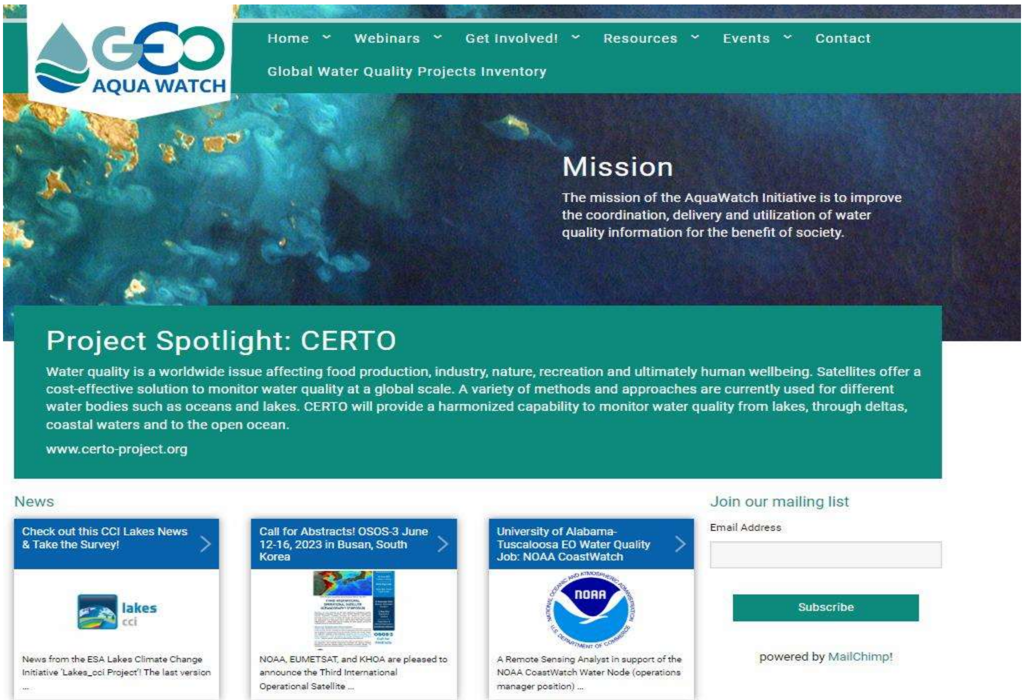

Figure 17. Location of the CMUG Integration & Climate Change Initiative Colocation in ESRIN, Frascati (Italy) from 24th to 27th October 2022.

Moreover, a direct contact with the GLEON network was established in the last four months, and one Science Lead of the Lakes CCI and I. Woolway will participate in the pertinent working group on Lakes_cci dataset established in the last weeks by GLEON: 1. Gap filling strategies; 2. Trends using 2D indexes; 3. Ice and cross-seasonal interaction; 4. Disappearing lakes; 5. Color and reflectance; 6. Ecological big effects; 7. Link to ISIMIP. For this latter, contributions are invited on i) lake model simulations under the ISIMIP protocol; ii) analysing publicly-available model output; iii) providing observational data to aid model calibration.

An update of the external conference attended by the consortium is listed below (

Table 13). This activity gave the opportunity to spread the information of the availability of the version 2.0.2 of the dataset which covers more than 2000 lakes.

Table 13 List of conference, with dates, partners and type of contribution, attended by Lakes_cci consortium in the period July 2021 to November 2022.

Event name	Type (workshop, conf, etc.)	Dates	Location	who attend?	Presentation /poster / chair
XXV AIOL CONGRESS	Conference	30/Jun-2/Jul 2021	Online	Mariano Bresciani, Gary Free (CNR)	Poster
SEFS 12	Conference	25-30/Jul/2021	Online	Gary Free (CNR)	Presentation

AGU21	Conference	13-17/Dec/2021	Online	J-F Crétaux	Presentation
LPS 2022	Conference	23-27/May/2022	Bonn, Germany	9 contributes from the partners	Poster/presentations
IOCCG-26 Committee meeting	Meeting	27-29/Jun/2022	Frascati, Rome	Claudia Giardino (CNR)	Presentation
RAQRS'VI	Conference	19-23/Sep/2022	Valence , Spain	H. Yésou	Poster
SISC 10th Annual Conference	Conference	19-21/Oct/2022	Rome	Giulio Tellina (CNR)	Poster
CMUG-Colocation	Meeting	24-27/Oct/2022	Frascati, Rome	Monica Pinardi, Rossana Caroni (CNR), Alice Andral (CLS), Stefan Simis (PML) and J-F Crétaux (LEGOS-CNES)	Poster
OSTST	Conference	31/Oct/22-04/Nov/2022	Venice	Anna Mangilli, Pierre Thibaut	Poster
XIV Assemblea annuale della Rete LTER-Italia	Conference	16-17/Nov/2022	Rome	Mariano Bresciani	Presentation

4.3 Requirements from the literature review

An update of the literature review to identify requirements for the lake science community was conducted respect to the last URDV2 (Aug. 2021; Phase 1).

To update the overview of the topic, we performed again a Scopus search with the keywords, "satellite" + "global lakes" + "climate change", for the time range from 2015 to date. A total of 729 documents (limited to article and review) were found, with a steep increase in the last 2 years (Figure 18).

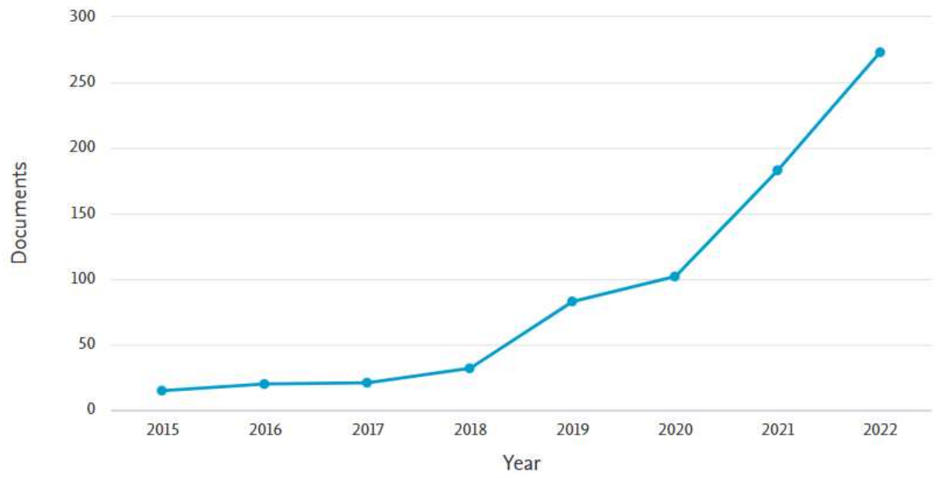

Figure 18. Published papers per year returned from Scopus search queries "satellite"+ "global lakes" + "climate change" from 2015 to 2022.

The main scientific journals in which the papers were published from 2015 to date are reported in Figure 19, and a brief overview of the main countries of principal investigators is shown in Figure 20. The main topics of the journals are remote sensing and water, and the main countries are China, US, and UK. On Nature Communications 13 papers were published from 2019 to 2022.

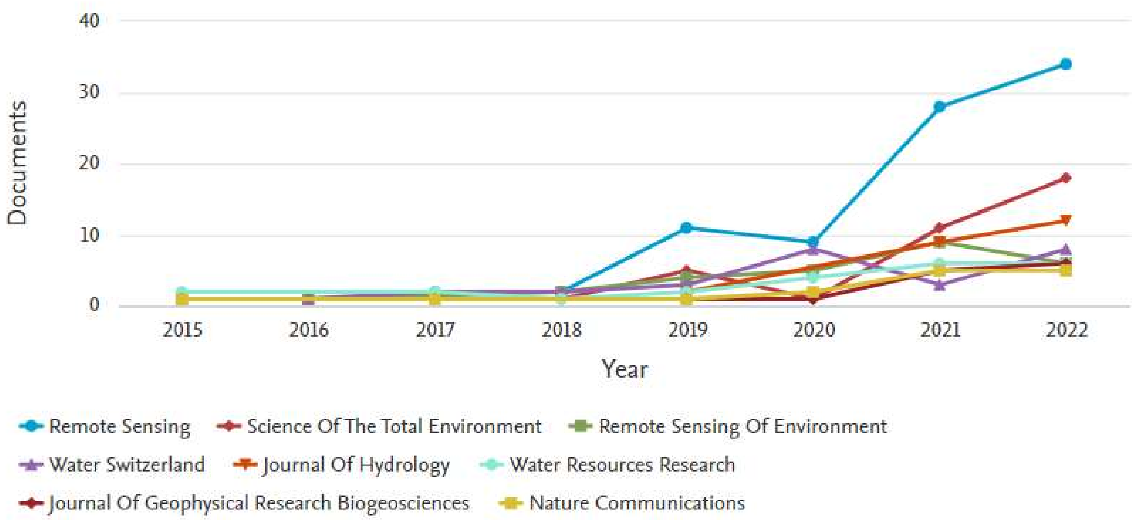

Figure 19. Distribution of publications returned from Scopus query for the main published journals for the period 2015-2022.

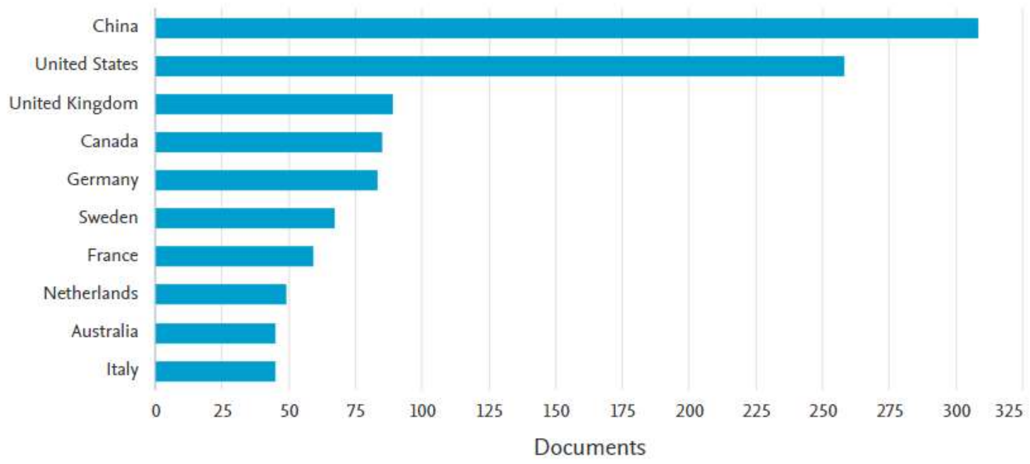

Figure 20. Distribution of publications by country/territory returned from Scopus query for the period 2015-2022.

Apart from the recent works of Woolway et al. that we already listed in the previous URDv2 (Phase 1) we can indicate the following papers among that published on Nature communications, which cover the compartments included in the IPCC 2021.

In the work of Karlsson et al. (2021), the authors investigated quantified C emission from inland waters (0.08–0.10 Pg C yr^{-1}), including the Ob' River (Arctic's largest watershed), across all permafrost zones of Western Siberia, and concluded that the important role of C emission from inland waters highlights the need for coupled land–water studies to understand the contemporary C cycle and its response to warming. Always for the Artic region, Feng et al. (2021) reported a larger and more heterogenous total water export (3-17% greater) and water export acceleration (factor of 1.2-3.3 larger) than previously reported for pan-Arctic rivers. This work and its results represent an updated and more accurate daily understanding of Arctic rivers exclusively allowed by recent advances in hydrologic modelling and remote sensing (by means of 155,710 satellite images, period 1984-2018).

A spatially-weighted global analysis of recent organic carbon (OC) burial in tropical lakes surrounded by highly productive rainforests at warm tropical latitudes (over ~50-100-years) that integrates both biome type and forest cover was performed by Amora-Nogueira et al. (2022). They found that tropical forest lake sediments are extremely important global OC sink (~80 Tg C yr^{-1}) with implications for the global C budget and consequences for climate change.

Anderson et al. (2021) studied the changes in lake Michigan stratification and found a shortened winter season results in higher subsurface temperatures and earlier onset of summer stratification. They concluded that shifts in the thermal regimes of large lakes will have profound impacts on the ecosystems of the world's surface freshwater.

Zhao et al. (2022) estimated the evaporative loss from global lakes (natural and artificial) which is a critical component of the terrestrial water and energy balance. The authors used satellite observations and modelling tools to quantify the evaporation volume from 1.42 million global lakes from 1985 to 2018. The main finding was that the long-term average lake evaporation is 1500 ± 150 km^3 yr^{-1} and that it has increased at a rate of 3.12 km^3 yr^{-1}. The trend attributions include an increasing evaporation rate (58%), decreasing lake ice coverage (23%), and increasing lake surface area (19%).

In the IPCC 2021 (Chap.8) is reported that from literature glacier lakes in general increase with melting glaciers (Linsbauer et al., 2016; Colonia et al., 2017; Magnin et al., 2020) but currently clear projections are not available.

In this context, Huang et al., (2022) quantified the response of lake ice to greenhouse warming to determine emergence patterns of lake ice loss using the Large Ensemble simulations conducted with the Community Earth System Model (v2). Their simulations showed that over the next 80 years the projected decrease on ice coverage duration will be of 38 days and the maximum ice thickness of 0.23 m. In addition, they found that in the Canadian Arctic, lake ice loss is accelerated by the cold-season polar amplification, while in the Tibetan Plateau, lake ice decreases rapidly due to a combination of strong insolation forcing and ice-albedo feedbacks.

The contribution of long-term variations in the seasonality of lake ice to surface water temperature trends across the Northern Hemisphere by means of satellite data and global-scale simulations was investigated by Li et al. (2022). They found an 8-day advancement in the average timing of ice break-up from 1979 to 2020 which influenced a widespread excess lake surface warming during the months of ice-off.

Instead, Pi et al. (2022) focused on the role of small lakes at global level characterizing lakes and their long-term dynamics to evaluate the associated impacts on water availability and carbon emissions. They mapped 3.4 million lakes on a global scale, including their explicit maximum extents and probability-weighted area changes over the past four decades. They found that the lake area increased (from the first period 1984-1999 to the second one 2010-2019) across all six continents, with a net change of +46,278 km^2, and 56% of the expansion was attributed to reservoirs. Moreover, although small lakes (<1 km^2) accounted for just 15% of the global lake area, they dominated the variability in total lake size in half of the global inland lake regions. In fact, the identified lake area increases over time led to higher C emissions, mostly attributed to small lakes. This study highlighted the emerging roles of small lakes in regulating not only local but also the global trends of surface water extent and C emissions.

4.4 Users and applications

From the analysis of the different sources of user requirements emerged differences in terms of user need depending on the applications.

Looking at the request of international panels, such as GCOS, a clear list of G/B/T is available (see section 3.1.1). From the Lakes_cci point of view the GCOS requirements are changing and seems more realistic targets with better suited metrics.

The main interaction was with the climate community, in particular modellers, and the feedback from the CMUG on temporal resolution of LSWT and LIC data and eventually of a coarser spatial resolution are requirements already discussed and currently are not into the scope of our project. In this case the trade-off between gap-filling coverage and technical feasibility is in favour of the latter. Currently the gaps in EO infrastructure, sensors characteristics and retrieval techniques can be identified as the main reasons of infeasibility to meet these requirements. A more strengthen collaboration with CMUG to discuss their future plans related to Lakes EVCs is an important point.

Apart from the needs of this community it was found by the survey that the wider community of user interested in lakes includes limnology, hydrology, ecology and biogeochemistry as disciplines of interest. The principal applications are in ecological modelling, understanding causes of environmental changes and assessment of trends. A promising support to user which is requested by many is the availability of tools/scripts and of video/tutorials to support the satellite products exploitation. Other requirements are related to a major cover in terms of number of lakes and of smaller size. Also, in this case it can be necessary to evaluate the trade-off between these two needs and their feasibility. A partial response will be done with the higher lake coverage by LWE (extension of hypsometry calculation using the Sentinel-2 mission) and LWL (new software (LPP) for small lakes, and new data product for historical missions).

In perspective in this Phase 2 of the project a cross-ECVs analysis and interaction with the CRG of other CCI projects (permafrost, glaciers, rainfall, LST, LULC, etc.), limnologists, and climate modelers should be developed. Few ideas can include the invitation of the CCI Science Leaders and of the Climate Science Working Group (CSWG), which is strictly related to CMUG, to our routinely meetings.

Finally, as the project itself aims to develop three main applications as defined in the use cases, inputs regarding main findings developed within each use case might be considered to expand this section. In particular, the requirements related to the following topics and thematic variables are expected:

- "Heatwave and storm events impacts on lakes" (use case #1: LWL, LSWT, Chl-a, Turbidity);
- "Water quantity in relation to water quality in a changing environment" (use case #2: LWL, LWE, LIC, LSWT, Chl-a, Turbidity);
- "Aggregated climate indicators for the global lakes data set" (use case #3: LWL, LWE, LIC, LSWT, LWLR, Chl-a, Turbidity).

5 Conclusions and future developments

User requirements analysis have been synthesised taking into account the statements of international bodies, interaction with CMUG and other CCI projects teams, literature review and one questionnaire circulated at the beginning of this Phase 2 of the Project.

The analysis presented in this document reflects the needs of a broad community of users with different application needs (e.g., climatologists, limnologists, and hydrologists). In such a complex framework, the requirements from GCOS (G, B and T) are in line with the characteristics of current or updated resolutions of Lakes ECVs. From GCOS documents is clear a need for gap filling in observation in parts of Africa, South America, Southeast Asia, deep oceans and polar regions. In the global warming context, the glacier/snow/permafrost evolution and changes have impacts on flooding, river and lakes. Regions in which such relationship needs further investigation are mountain regions, and in particular in the Tibetan Plateau, Patagonia, Peru, Alaska and Greenland. The combination of LWL and LWE can be crucial in water volume/mass estimation. The LSWT and LIC variables are of extreme interest for regional climate models both as input and for validation purposes. An effort can be done in interaction with CMUG to develop a proper experiment which include Lakes ECV. Therefore, Lakes ECV can be involved in studies aimed at filling the knowledge gap in carbon and methane budget (e.g., LWE, LWLR), water cycle changes and budget (e.g., LWE, LWL) and energy balance budget (e.g., evaporation, lake effects on wind). The estimate of lake storage change can be useful for water storage, water availability and water cycle budget calculation, and for glacier lake volume estimation.

The third survey was more focused on feedback derived by users that managed the Lakes_cci dataset. Some suggestions regarded the need of pre-processing the data (e.g., gap filling, outliers' removal), to have the possibility to download a sub-set of the dataset, to increase frequency and the number of lakes, and to resolve inconsistency for some products. An interest was shown for new thematic variables such as CDOM and extinction coefficient. Another important point is the need to reduce the processing and observational expertise needed to exploit the data successfully. New script and tools, video and tutorial will be made available. A FAQ section on the Lakes project website will be developed to make useful for a wider community of users the reply to common issues.

In the next months a wider scientific community is expected to be reached, thanks to the improvements of the latest version of the dataset (v2) such as spatial coverage at global level for all variables, and to the recent interaction at CMUG and Colocation meeting and with GLEON network (Lakes_cci working group). In this latter context a link to ISIMIP can be of crucial importance.

A step forward should be done to have Lakes ECV included in a sustainable production system and to support climate services. In fact, interoperability between CCI ECVs and climate services (e.g., C3S) is a clear requirement to support ECV products dissemination and knowledge exchange.

The future user workshop (spring 2024) will be an opportunity to collect/revise the needs from an international well focused community on climate modelling and will be probably organized jointly to another meeting/workshop, as done for the Phase 1 of the project.

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