D1.1 User Requirement Document (URD)

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LIST OF CONTENTS/SOMMAIRE

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 user requirements for the European Space Agency Lakes Climate Change Initiative (CCI) project (Lakes_cci, http://cci.esa.int/lakes).

This report synthesises information obtained through (1) review of existing reference documents and scientific literature, (2) CMUG Integration and Colocation meetings held in 2022 and 2023, and (3) interactions with the wider lakes research community. Results are also included from the third user requirements survey (https://climate.esa.int/en/projects/lakes/news-and-events/news/third-users-survey/) and from two dedicated user workshops, the Physical Processes in Natural Waters workshop held in Girona (1-5 July 2024) and the 7th LAKES Workshop on Parameterization of Lakes in Numerical Weather Prediction and Climate Modelling held in Milan (20-22 November 2024). Preliminary results of an additional survey related to the foreseen water transparency product foreseen are also presented.

The revised GCOS requirements for the Lakes ECV (GCOS-245) are considered achievable by the project consortium. More broadly, the Assessment Report 6 (AR6) of WG1 of the IPCC emphasized the importance of Lakes ECV Products in improving knowledge on the carbon and methane budget, water cycle and energy budgets, which are activities cutting across several CCI projects including Lakes_cci. The 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). The 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., data analysis scripts, tools, tutorials) to exploit the data successfully would also be welcomed. The latest climate data record (CRDP V2.1.0) of the Lakes_cci project was published in July 2024. Thus, the collected requirements may not yet be fully representative of the collective experience of the user community using this latest version compared to previous releases. However, we note significant uptake of the Lakes_cci data, which is expected to generate further feedback.

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 the visible and near infra-red solar energy flux returned by surface waters, and of biogeochemical processes and habitats in the illuminated 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 3 (GCOS and IPCC WG1). This section also focuses on the interaction between Lakes_cci and the Climate Modelling User Group (CMUG).

Section 4 reports requirements from the wider lakes expert community. This section illustrates the results obtained by circulating our third survey, provides an overview of requirements from scientific literature, and summarizes the dissemination activities of the project. A 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 feedback mechanisms 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.

It is important to remember that this is a synthesis of what is needed and not a statement of what will or can be achieved by satellite observation. The requirements for the Lakes ECVs and their products are presented below in Table 1 for LWL,Table 2 for LWE, Table 3 for LSWT,
Table 4 for LIC, Table 5 for LIT, and Table 6 for LWLR.

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				

It should be noted that the Lakes_cci 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. 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

ECV	Item needed	Current	Updated
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 °C / decade
	horizontal resolution	300 m	10 m-5 km2
	temporal resolution	weekly	3 hours-10 days
	timeliness		1-365 days
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	1-15 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% at peak waveband
	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

In the following, an update of the currently achieved GCOS requirements and an analysis of the remaining gaps for the six Lakes ECVs is reported.

- LWL: Temporal resolution and uncertainty are not yet met for all lakes. Potential use of laser altimetry and new ESA thematic datasets will help to reduce uncertainty. Uncertainty requirement is achieved for medium and large lakes, and uncertainty is lower with recent satellite missions. Lakes that are not yet visible with nadir altimetry can be processed with SWOT in future.
- LWE: horizontal resolution requirements achieved with Sentinel-2, temporal resolution depends on time resolution of satellite altimetry (1-35 days), the uncertainty is then in the order of 1% in nearly all lakes processed.
- LSWT: horizontal resolution of 1 km (breakthrough level) is achieved, and future high resolution sensors such as Trishna may be used for gap analysis. Temporal resolution and uncertainty requirement achievement depends on the lake. It will be possible to include more sensors where and when available and analyse nighttime LSWT to improve these characteristics.
- LIC: horizontal resolution threshold (1000 m) is achieved, the temporal resolution of 1 day breakthrough will be achieved with gap filling, and the measurement uncertainty threshold (10%)

is achieved. In the CRDP v3.0, LIC will include information on the measurement uncertainty that need to be amalgamated on a per-lake basis.

- LIT: horizontal resolution threshold (10000 m), temporal resolution breakthrough (30 days), and measurement uncertainty of 10 cm are met with altimeter data acquired in Low Resolution Mode (LRM). Recent advances in the processing of unfocused SAR data are expected to improve the horizontal resolution to 350 m (breakthrough) and measurement uncertainty to 5 cm.
- LWLR: the GCOS uncertainty requirements was not met in v2.1, with chlorophyll-a and turbidity both exceeding the threshold. The update v3.0.0 algorithms are expected to offer significant improvement, based on atmospheric correction updates that better resolve turbid water. Uncertainty characterization is also being revised following observations that systematic negative bias has been largely resolved.

It is worth mentioning that GCOS has started working towards harmonizing the variables across several ECVs as well as rationalizing the set of variables withing each ECV. This is an ongoing process to be developed in 2025-26 that the Lakes_cci project will monitor.

3.1.2 Requirements from Intergovernmental Panel on Climate Change (IPCC) WG1

IPCC Working Group 1 (WG1) 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 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.

[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.

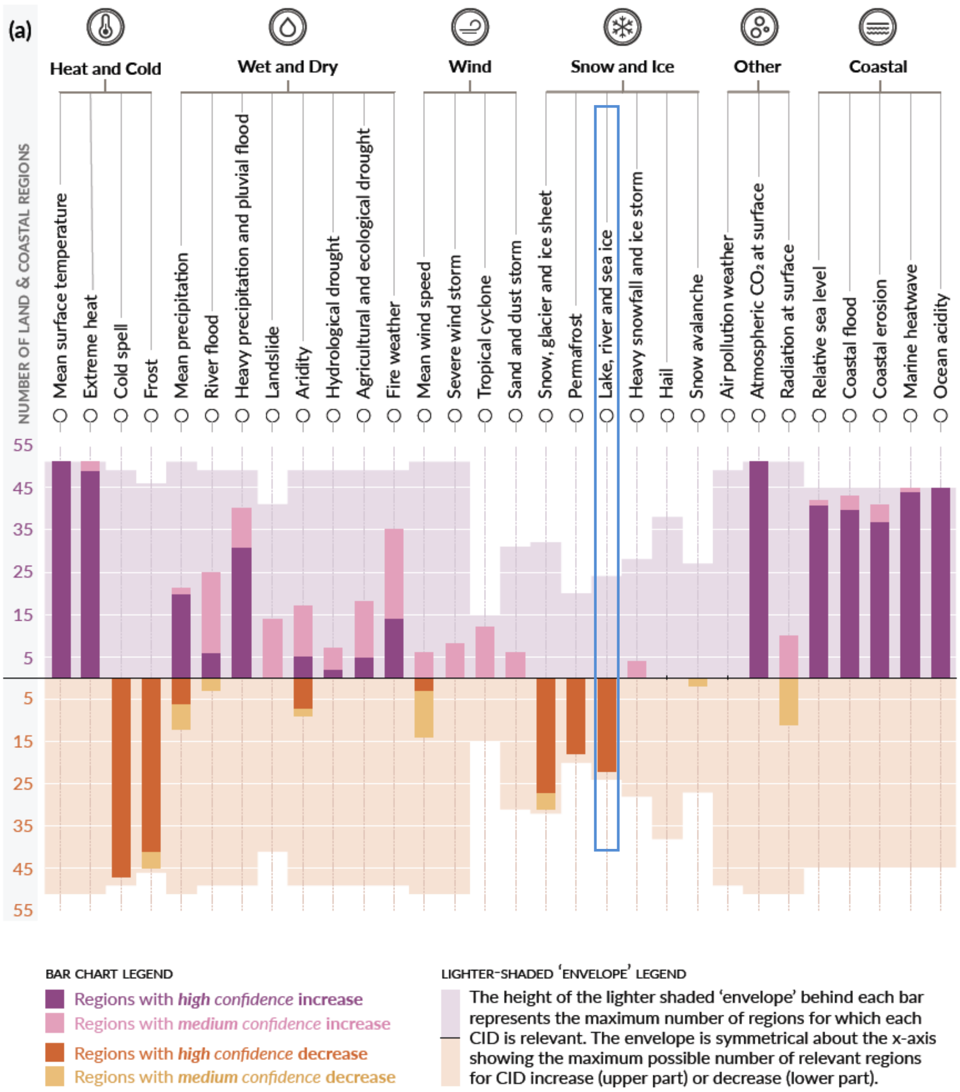


Figure 2. Synthesis of the number of AR6 WGI reference regions where climatic impact-drivers are projected to change. Panel (a) shows the 30 climatic impact-drivers (CIDs) relevant to the land and coastal regions grouped into six types: heat and cold, wet and dry, wind, snow and ice, coastal, and other. 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 139,000 km^2 of inland water areas have become land, while creation of dams has converted about 95,000 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 CO2 and CH4 budget improvement and is linked to water cycle budget, as influence and is influenced by permafrost change, and is directly impacted

[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

in an 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 (<1km2) 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 CO2) and 37% (for CH4) 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.

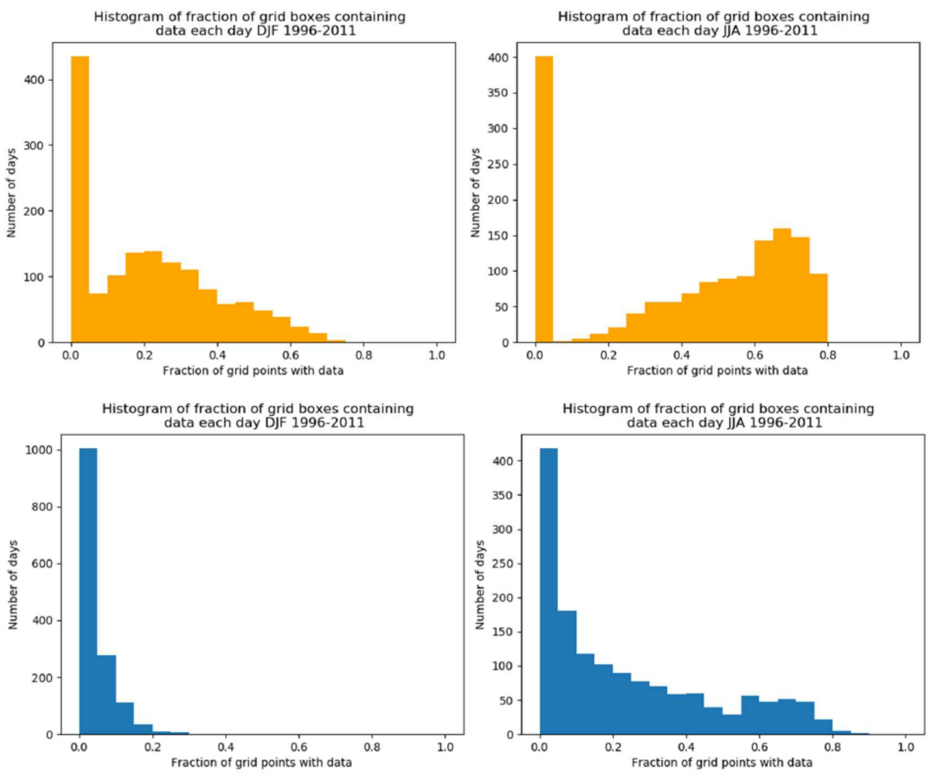


Figure 3. Histograms of the fraction of grid boxes containing data (i.e., not missing) each day in the European RCM domain for the period 1996-2011 LIC (orange) and LSWT (blue) (from Deliverable 3.1 of CMUG)

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.

A presentation on WP3.7 "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 co-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 co-leads are reported in Table 9.

3) Where/what are the data gaps: ECVs, EO data, in situ data. Comments from Lake Science Leads are reported in Table 10.
4) 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 ECVs (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 ECVs) 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.

3.2.3 13th CCI Colocation & CMUG Integration meeting (2023)

From the last "13th CCI Colocation & CMUG Integration meetings" held in Oxford between 7th and 9th November 2023, the following summary focus on item useful for user requirement analysis.

- Since March 2022, the WCRP CMIP-IPO and the ESA Climate Office have been colocated. It offers a fantastic chance to strengthen the connection between the modelling and climate observation groups. The planning for CMIP's contribution to the IPCC's seventh cycle of assessments has commenced subsequent to the conclusion of the sixth cycle. An update on current CMIP operations was given. This included information on the preparations for CMIP-7, including the timetable and planning, as well as interactions with other WCRP programs including the Earth Systems Observation and Modelling (ESMO) project. The development and consultation of realm variables for the CMIP Data Request is open to CCI science leaders.

- The GCOS Revised Implementation Plan (2022) specifically recommended that more emphasis be placed on merging individual ECVs to address unresolved challenges in the energy, water and carbon cycles. This proposal was the main topic of the cross-ECV session. The combined GCOS-WCRP workshop on energy, carbon and water cycles was summarised and comments were made. The main issues to be addressed in each cycle were identified during the workshop and a report is being prepared.
- Session on emerging topics started with a summary of recent developments from the Space Summit with "Green & Sustainable Future" as one of the three main themes, and an update on ESA's accelerator "Space for a Green Future". CCI Science Leaders welcomed this overview, which linked CCI activities to a wider European development in the field of climate, and the increased inclusion of climate science in the Candidate Science Questions. The CCI Science Leaders expressed interest in this session's continuation, which focused on a new subject for the program: adaptation actions under the UNFCCC Paris Agreement. This served as an introduction to upcoming initiatives in this field. An overview of the GCOS Adaptation Task Team was given by the GCOS Secretariat. GCOS plans to host one or more workshops with leading adaption implementers and subject matter experts in order to discover global datasets, ECVs, and climate data, including the spatial and temporal requirements for adaptation. When questioned about the amount of satellite data needed for adaptation, GCOS recommended using high-resolution space-based observations (≃10m) to design adaption actions and monitor changes at the local scale. Expanding on ESA's adaptation strategies, a summary was given of the many applications of satellite data for health adaptation, highlighting the expertise and accessibility of these data. Despite the drawbacks of using space data for adaptation, successful adaptation depends on policy makers having a better understanding of the data and access to ready-to-use data. In addition, the spatial and temporal resolution of the data is crucial for very local applications.
- With the aim to encourage cross-project collaboration, a poster session was held highlighting recent achievements of each project.
- The CMUG Integration session began with an overview of the new 3-year phase of CMUG focused on the consortium partners and on the main work packages of the project. This was followed by a summary of the planned CMUG science studies using CCI ECV data in the context of climate models.

3.2.4 14th CCI Colocation & CMUG Integration meeting (2024)

CMUG feedback

The first day of the CMUG Integration was dedicated to the presentation of the new Phase 2 of the project started last year, and the update of 8 scientific studies using 21 ECVs, not focused on Lakes ECV. A new version of the "D1.1: Climate Community Requirements" is available (May 2024), but there is no specific update for lakes compared to the previous version of August 2022. A general outcome was to continue and improve the interaction between modellers and EO data producers, with a closer relationship and not just communication about where the data are stored.

From the CMUG interview the group reported some user requirements that can be generalized also for Lakes_cci:

- top level content list with dataset specification;
- dataset regularly updated;
- consistency in file format resolution metadata data accessing documentation;
- Quality Control (QC) described in metadata;
- comparison of different datasets and guidance on applicability

- higher resolution;
- tools to subset and manipulate the data before download;
- cloud computing environment to minimize data transfer and storage.

CCI Colocation feedback

CLIMATE-SPACE Knowledge Exchange

The new Knowledge Exchange project is under the CLIMATE SPACE umbrella and is starting now. Therefore, a brainstorming was held to get new input/needs from CCI projects in terms of website, storytelling, education, data dashboard/open data portal and CCI toolbox.

Climate Data Store

The updates from the Copernicus Climate Change Service (C3S) include a new fully modernized release of the climate data store, and the current offer of the climate data records of ECVs. In fact, from our project now we have Lakes ECV included as LWST (1995-2023), and LWL (1992-2023). In addition, simplified documentation is now available on the Climate Data Store website (https://cds.climate.copernicus.eu/), together with a user-oriented evaluation and quality control function.

Uncertainty inventory

During the 14th colocation meeting, ECV science leads discussed discrepancies in how ECV Product uncertainties are reported to users and assessed against GCOS targets. Whilst it was acknowledged that there is no single methodology to suit the characterisation of uncertainties across remote sensing domains, there was concensus that methodologies should be harmonised where possible, and that users be informed on how uncertainty products should be interpreted. In the Lakes_cci, a similar discussion already took place, resulting in revision of quality flags versus uncertainty product naming. It was observed that several studies (including those originating from the Lakes_cci) used uncertainty as a proxy of data quality, which may introduce unexpected biases in their analyses.

On this issue it emerged that for example the LST (Land Surface Temperature) project has a tool to propagate uncertainties on cci. Another point that arises is the need to encourage user to use uncertainty and not only trend.

ECV Rationalisation

GCOS reported on their review of the relevance, feasibility and cost-effectiveness of the 55 ECVs, including 177 ECV Products. The grouping of products among variables is assessed to promote transparency and confidence. Any changes agreed following this process will inform the next framework from 2028. In the currently proposed topology, 42 ECVs are identified after regrouping and renaming. The process is of interest to the Lakes_cci, being a thematically grouped set of products combining multiple observation domains, and benefiting a wide user community. User requirements collected within Lakes_cci can now be brought into the consultation process via the project team, under ESA as one of the organisations being consulted. The changes for the Lakes ECV are the proposed addition of subsurface lake temperature, whilst lake water-leaving reflectance would be brought under a global albedo assessment. Initial considerations with regard to the proposal include (1) that subsurface temperature would benefit from knowing the input from albedo (i.e., K_d), which is already being experimented on in the current Lakes_cci team, that (2) the Lakes_cci only delivers on a subset of lakes globally, and that accurate albedo estimates will not be feasible for the majority of small lakes. Additionally, differences in the definition of albedo versus reflectance were pointed out, as these are not interchangeable. A degradation in the ease of use from combining current lake colour products with ice, temperature and water level estimates, as demonstrated in use cases and externally led work, would likely occur if any one of these products is produced on different timescales. Advantages may also be identified as a result of the current assessment by GCOS, notably in having a (more) complete albedo product at the global scale, for terrestrial climate modelling. Further input from users will need to be sought from the Lakes_cci user community to provide feedback to ESA and ultimately GCOS.

Lastly, during the presentation of the Outcome from the CLIMATE SPACE cross-ECV call, it emerged that in MOTECOSUMA (= Monitoring the energy cycle for a better understanding of climate change) project, lakes and soil moisture variables for hydrosphere are likely to be source to study the Earth Energy Imbalance (EEI).

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 (Figure 5. Webpage of the third questionnaire on the use of the ECV Lakes.Figure 5) (**https://docs.google.com/forms/d/e/1FAIpQLSfISKdABrphLcMSu-UhEd_Wev16Pj72OGu3D9wySjXMRhz5xQ/viewform**). It is focused on the use of the dataset produced in the Phase 1.

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 for the period from January 2023 to October 2024.

Until 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 4.4 we also report the dissemination activities.

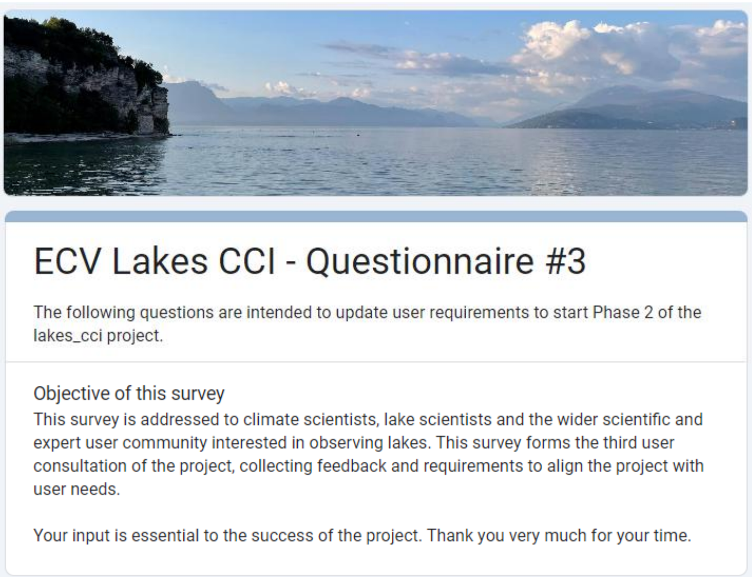


Figure 5. Webpage of the third questionnaire on the use of the ECV Lakes.

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**

Method	Users	Datasets	Number of accesses	Size	Activity days
anon-ftp2.ceda.ac.uk	2	1	2	1.71 KB	2
cci-thredds-download	46	1	2.325	127.25 GB	191
cci-thredds-subset	14	1	410.897	207.3 GB	40
dap-thredds-download	40	1	435.229	2.33 TB	58
ftp3.ceda.ac.uk	2	1	20.047	1.64 TB	4
Totals	**100**	**1**	**868.500**	**4.31 TB**	**295**

Figure 6. Method, users, number of accesses, size and activity days related to the Lakes_cci dataset (period: 01/01/2023 to 22/10/2024).

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).

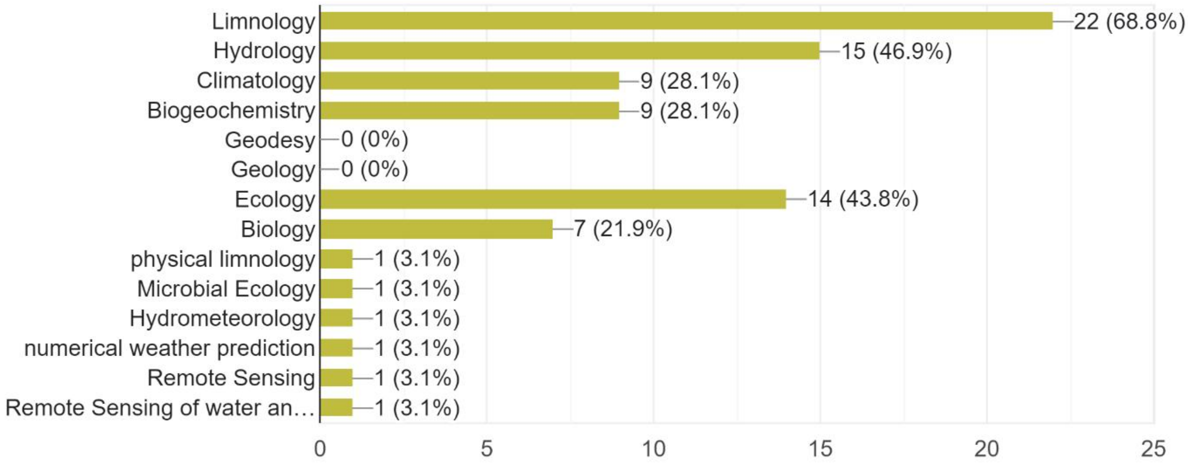


Figure 7. Histogram of answers to question 1.

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).

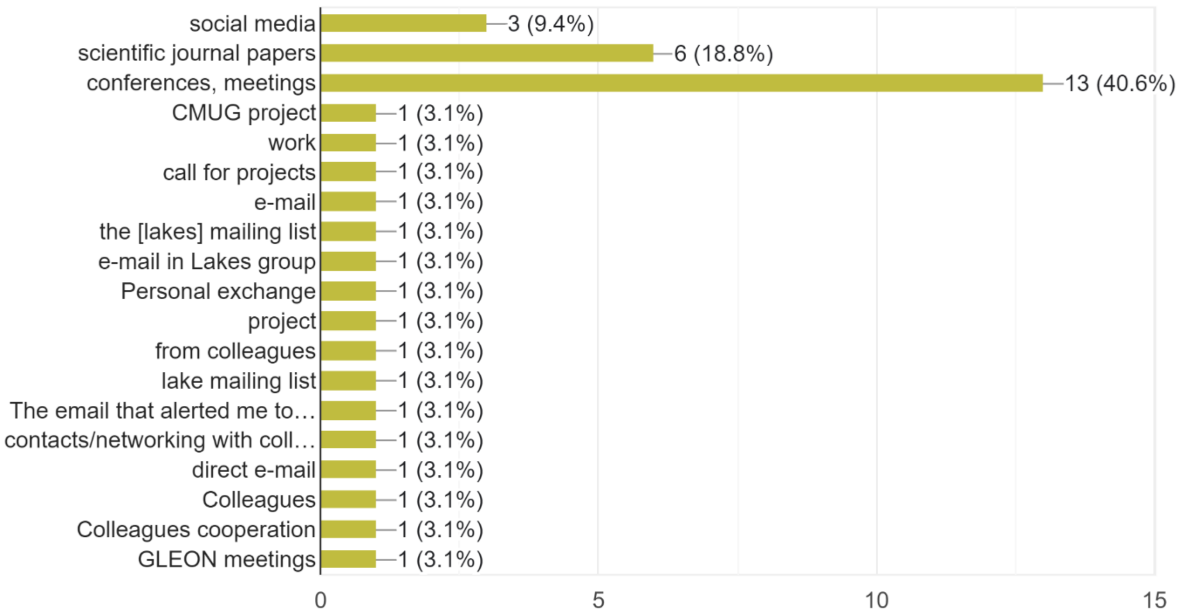


Figure 8. Histogram of answers to question 2.

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

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

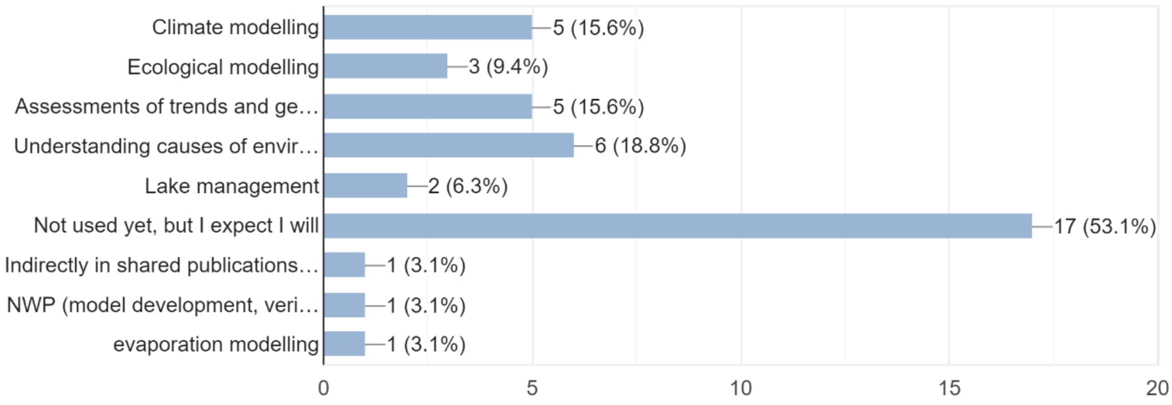


Figure 9. Histogram of answers to question 3.

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).

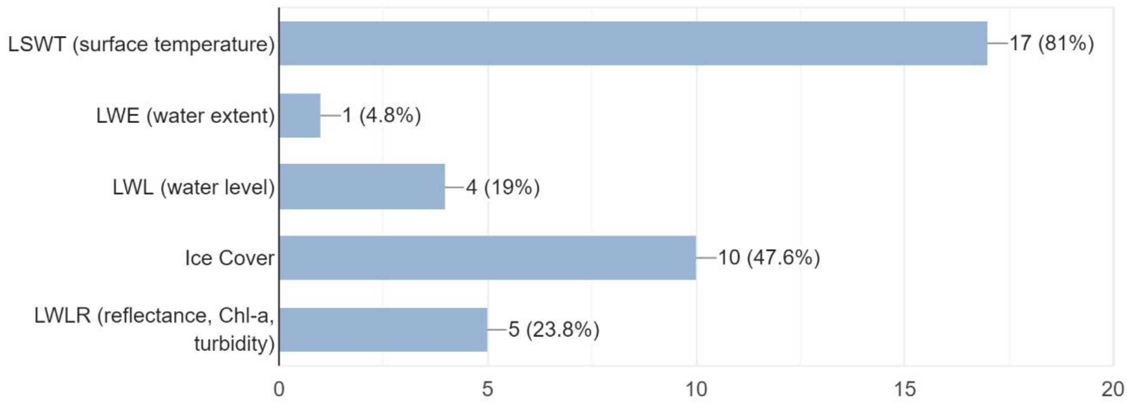


Figure 10. Histogram of answers to question 4.

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).

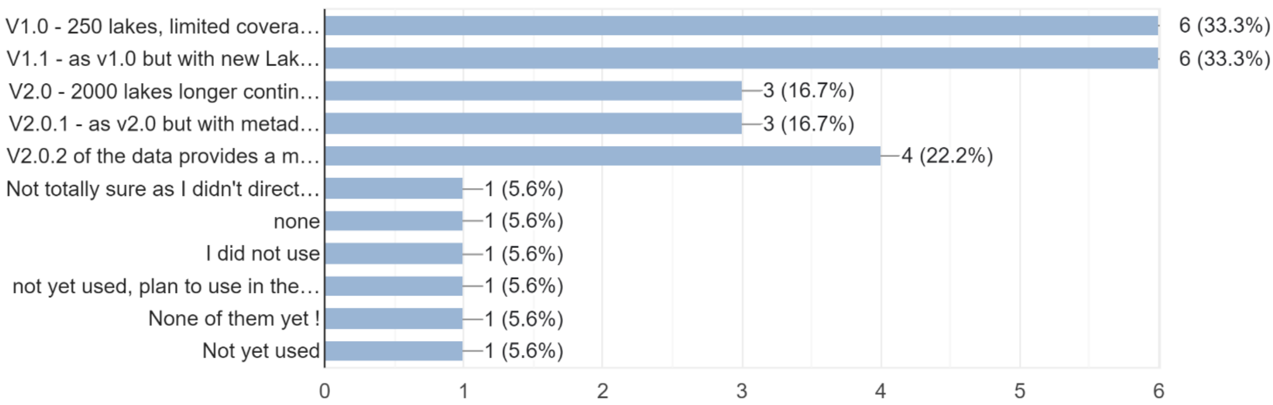


Figure 11. Histogram of answers to question 5.

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 positively.

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).

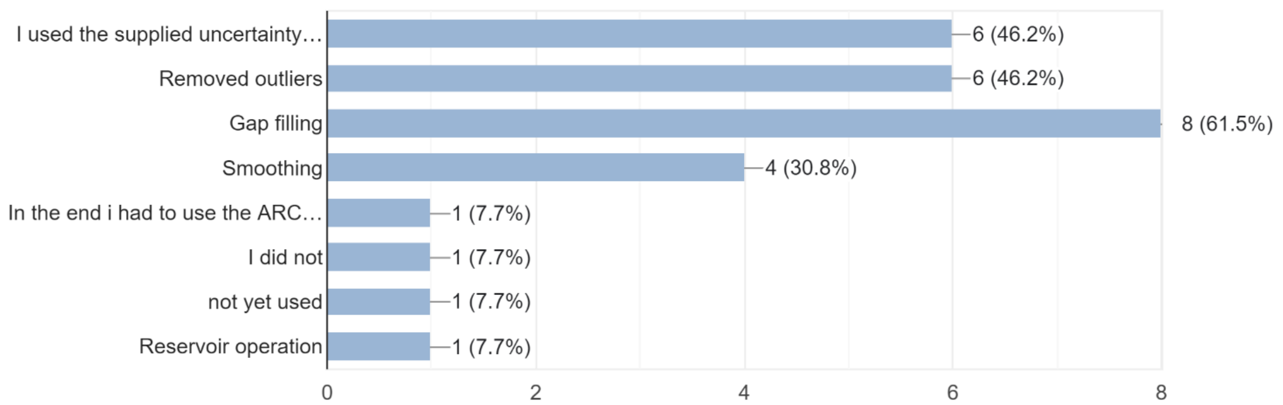


Figure 12. Histogram of answers to question 9.

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).

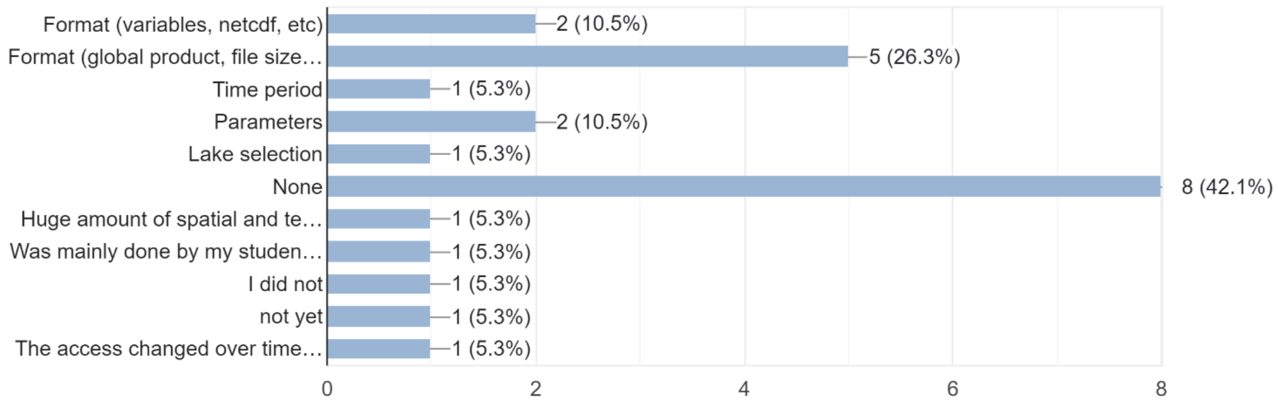


Figure 13. Histogram of answers to question 10.

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%).

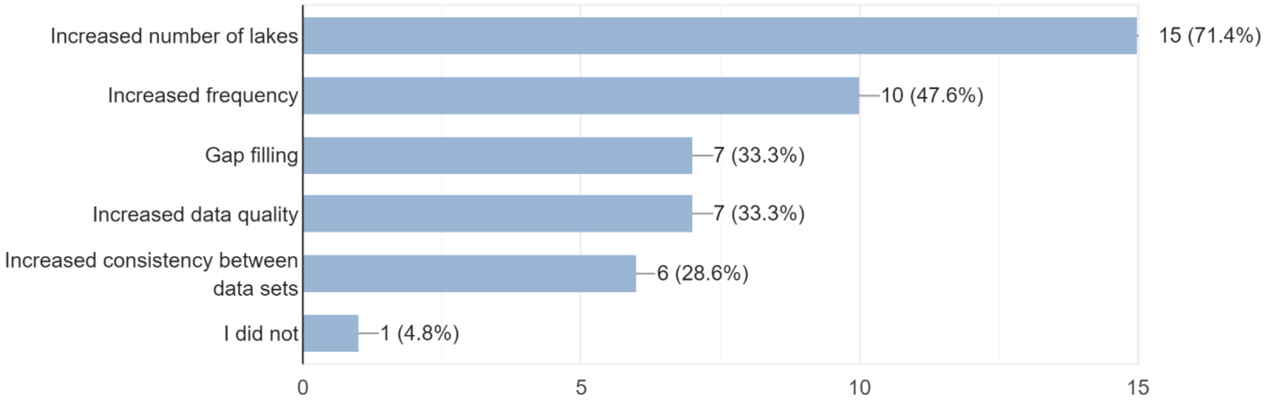


Figure 14. Histogram of answers to question 12.

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).

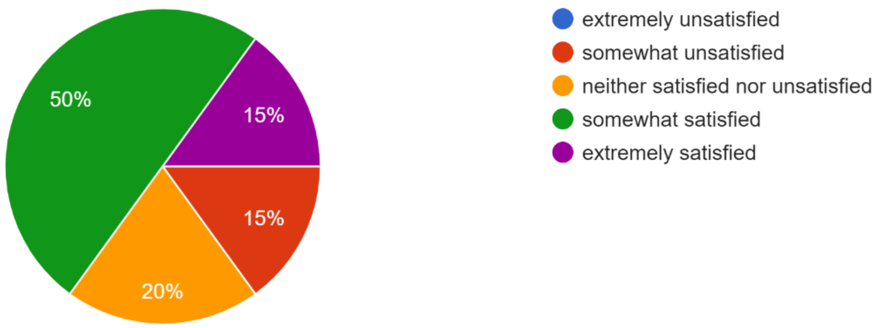


Figure 15. Pie chart of the answers to question 14.

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 (K_d), 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).

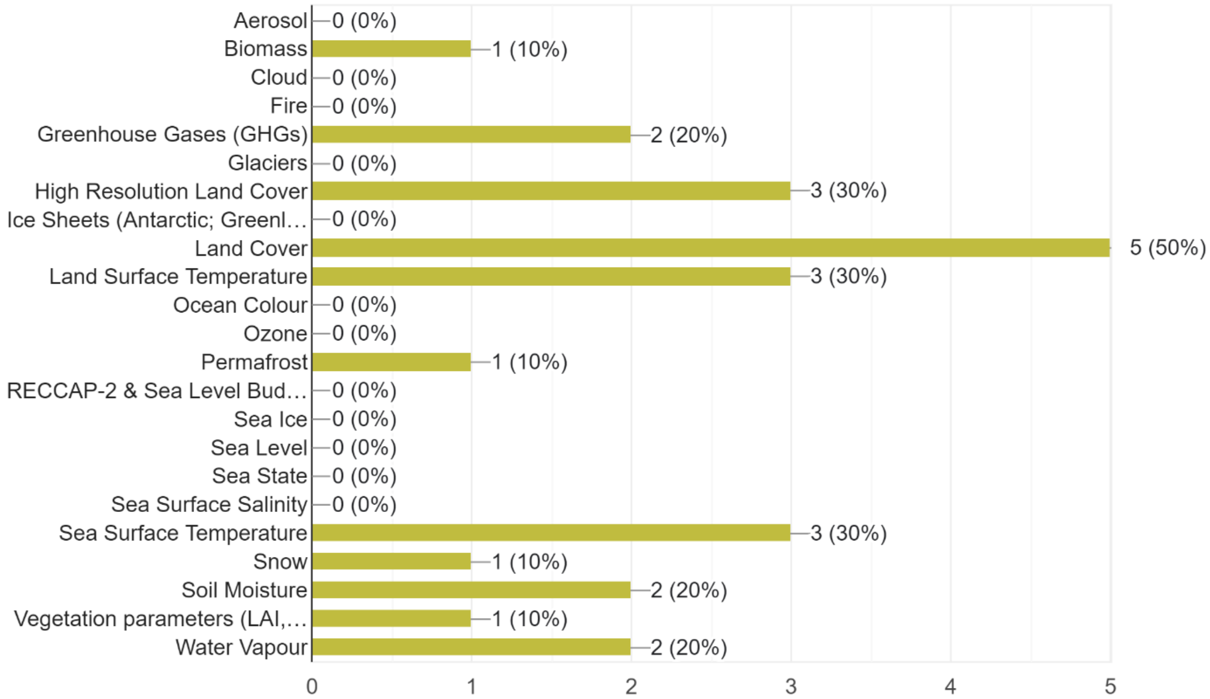


Figure 16. Histogram of answers to question 18.

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 requested to be developed can be CDOM, K_d, and lake volume change. 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)

At present, some important points achieved or on-going by the project which move towards meeting user requirements are the following.

- A new variable, Lake Ice Thickness (LIT) is available for a single lake (Great Slave) in the v2.1.0 data release and is provided in a separate file.
- Key improvements made to the ECV Products, compared with the previous dataset, include:
  - Lake Water Level: Spatial coverage increased to 498 lakes as well as improved temporal coverage using data from past satellites. This represents approximately 50% of the number of lakes inspected for satellite observation of sufficient quality, to date (921 lakes investigated in total). A product quality variable has been added.
  - Lake Water Extent: Spatial coverage increased to 207 lakes (from 84 in v2.0.2). The LWE data are directly linked with LWL observations, for lakes where a hypsometric relationship has been established. Thus, lakes where LWL are not available also do not have LWE estimates.
  - Lake Water Leaving Reflectance: improved quality control in periods with ice cover, by clustering the observations of chlorophyll-a and turbidity in relation to LSWT climatology, masking outliers when low temperatures suggest (thin) ice cover is likely. In addition, spectral filters are used to determine the likelihood of adjacent land interfering with lake colour observations. A quality flag has been added describing several data quality risks. For 48 lakes, MODIS-Aqua have been processed to fill the observation gap between MERIS and OLCI instruments. Work is also underway to include CDOM and K_d in future releases.
  - Lakes Surface Water Temperature: reprocessed SLSTR-A and SLSTR-B. The reprocessing improved quality, reduced uncertainty and slightly increased the number of observations (in time and space) since all the SLSTR-A and SLSTR-B L1b files were NTC (Non-Time Critical) and therefore consolidated.
  - Lake Ice Cover: increased temporal coverage for all lakes.

- Lake Ice Thickness: the number of lakes selected for the retrieval of LIT from radar altimetry in LRM (Jason 1/2/3 satellites) will increase from a single lake (Great Slave Lake) in CRDPv2.1 to 13 lakes across Canada for CRDPv3.0, providing a relatively long (20+ years: 2001-2023) historical time series for climate studies. There has been a dramatic decrease in the number of lakes globally where LIT measurements are reported on a regular basis. There is a pressing need expressed by the lake ice community (e.g. Lake Ice Workshop held 6-9 February 2023 in Madison, Wisconsin, USA) to not only maintain the current in situ network of lake sites but to expand the spatial coverage from satellite measurements that lakes_cci can provide.

Two relevant project extensions focus on CDOM quantification and Lake Storage Change (LSC), respectively. . A technical report on CDOM retrieval can be found on the project website (CDOM Techinical Note). This includes information on in situ data collection, algorithm comparison and testing, evaluation and selection of published CDOM algorithms, and recommendations for water body types. It also includes a list of optical water types for which existing CDOM algorithms can provide CDOM and areas where further research is needed to improve the accuracy of CDOM estimates.

The Lake Storage Change Option is working on the development of the LSC retrieval methodology and will be applied to a subset of the lakes included in the Lakes_cci dataset, with a target of at least monthly resolution with an uncertainty of <10% of the lake volume, in line with GCOS and user requirements. Further information is provided in the "State of the art" and "User requirements" available through the project website.

4.2 User workshops

The Lakes_cci User Workshop was organised as a sub-workshop of the "26th Annual International Workshop on Physical Processes in Natural Waters (PPNW2024)", held in Girona, Spain, from 1 to 5 July. The session "Remote Sensing in Lakes" was held on the afternoon of Friday 5 July. PPNW2024 was attended by 54 participants from different countries, of which about 25-30 participated in the sub-workshop, providing an opportunity to meet the engineering, atmospheric and physical science community on lakes. The summary of the session and the feedback collected during the workshop have already been reported in the document "D5.3. User Workshop Document (UWR) - 3.0r1" (CCI-LAKES2-0044-RP). The main results obtained from a fairly homogeneous end-user community focused on physical limnology and processes are that this is a community not used to using satellite data, but that there is a certain interest in high quality and high spatial resolution ECVs for individual lakes, with particular interest in temperature, water quality, lake level and ice cover data, with the possibility of using Lakes_cci data in the near future.

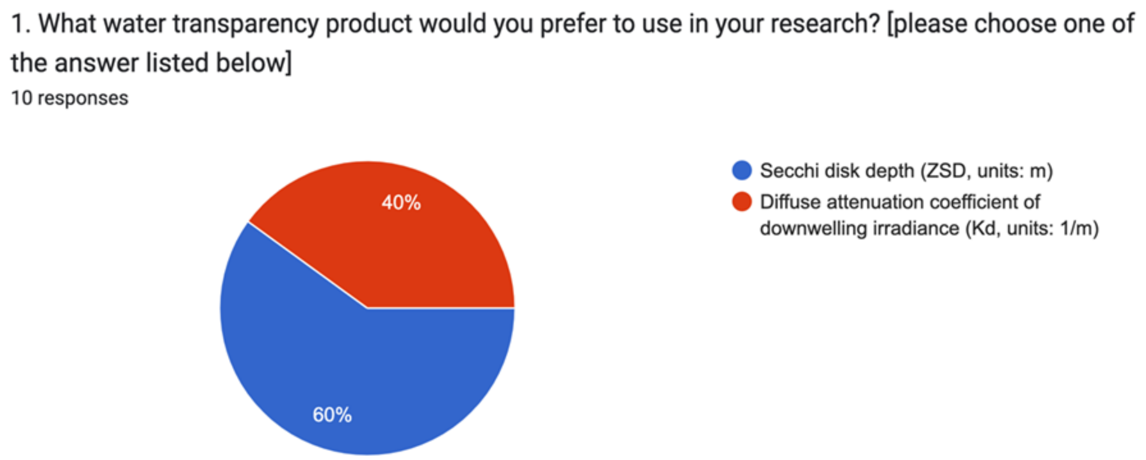
Another user workshop was organised in autumn 2024, namely the "7th LAKES 2024 Workshop on Parameterisation of Lakes in Numerical Weather Prediction and Climate Modelling", that was held in Milan from 20 to 22 November (https://lakesmilan2024.irea.cnr.it/). The Workshop, in continuity with the first Lakes_cci user workshop, held in Toulouse in 2019, aimed to bring together scientists working on different aspects of the lake-atmosphere feedbacks and the interaction of lakes with regional and global climate. The workshop was announced throughout the Lakes_cci webpage and by the GEOAquaWatch Network. Invitation emails were also sent by the Scientific and Organizing committees, and by the CMUG project manager to their communities. The summary of the workshop and the user feedback have been reported in the document "D5.3. User Workshop Document (UWR) - 3.0r1" (CCI-LAKES2-0044-RP). The great usefulness for Numerical Weather Prediction (NWP), climate studies and related applications of having a lake water transparency dataset from remote sensing observations with global coverage became apparent. The extinction coefficient could improve the model estimation of lake surface temperature in the lake warming regime. There was also good interest in the Secchi disk depth as a variable for this lake parameterisation community. The ongoing task of filling the LIC and LSWT data gaps was also appreciated by this lake modelling community. The critical role of transparency in the development of the convective mixing layer under the ice was also highlighted.

4.3 CCN9- Lake water transparency product survey

At the beginning of Option CCN9, a survey on water transparency products was designed by the University of Stirling and Plymouth Marine Laboratory, and a preliminary collection of results is presented in this document.

The survey consists of 7 questions and aims to understand user requirements for lake water transparency product(s) in climate datasets. The survey was mainly sent to the lake physical modelling community, including (1) the CNR group (2) Iestyn Woolway's group from Bangor University, (3) the lake modelling group in GLEON (4) attendants of the Lakes_cci PPNW 2024 workshop who agreed to receive the Lakes_cci newsletter (5) attendants of the recent 7th Lakes workshop. Ten replies have been received from September 2024 to date, but the number of replies should increase thanks also to the publicity given during the recent 7th LAKES workshop.

A brief overview of the questions, answers and comments is given below.



2. If you can, please explain your preference briefly:

8 responses

Both are same important for my research.

To relate chl-a to the euphotic zone

Kd is a more meaningful unit of measure. If I only had Secchi I'd have to convert to Kd and methods of conversion are only approximations.

Kd-Sd relationships vary per lake, and Kd is more meaningful. However, Sd is measured more often, so would facilitate comparison with observations. I see value in both, but I would prefer Kd due to it's higher ecological relevance.

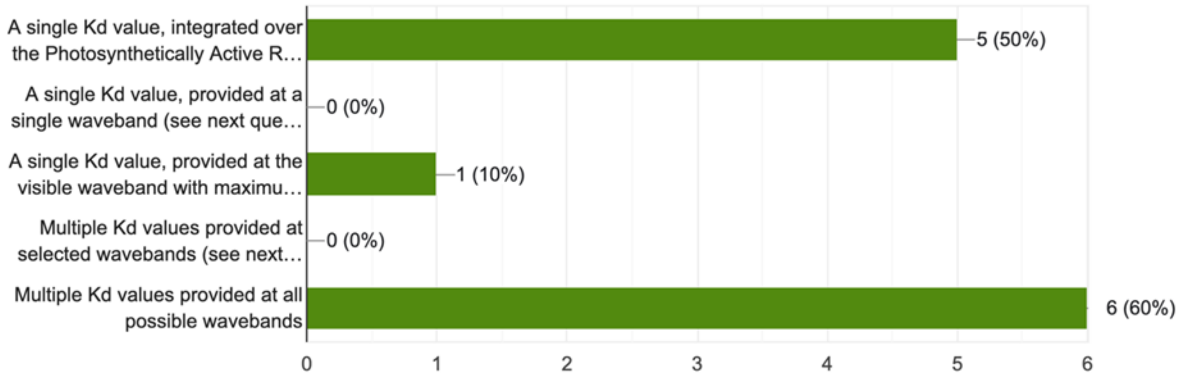
I'd rather use Kd and estimate Secchi depth than the contrary. However, for some applications, I suspect a Secchi disk depth product would attract a broader community of limnologists.

worked with Secchi depth so far - mgiht work with Kd in the future though

easier to compare to in situ measurements

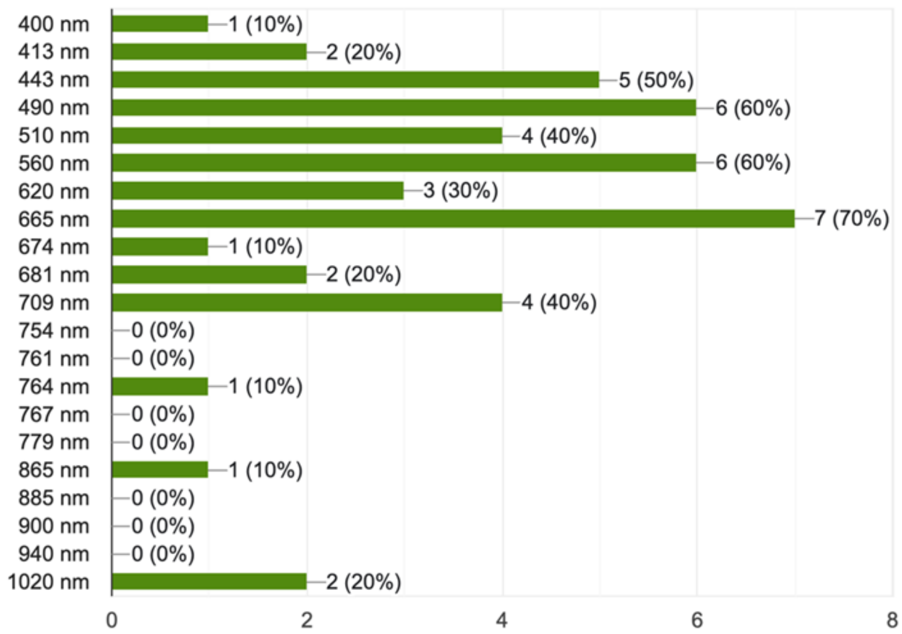
3. Regardless of your preference stated in the previous question, in what form should a diffuse attenuation coefficient of downwelling irradiance (...ted to be useful to you? [multiple answers allowed]

10 responses

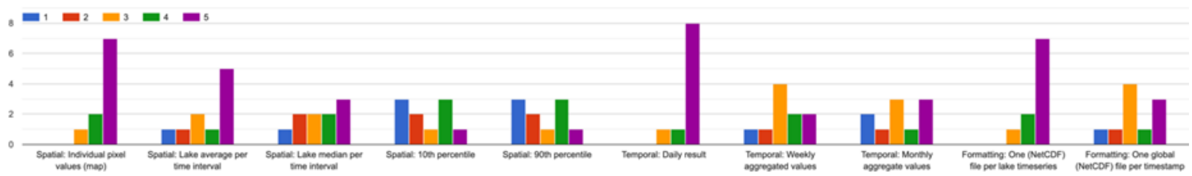


4. Which waveband(s) would you prioritise if Kd were to be provided for a selection of wavebands? [up to 5 answers allowed]

10 responses

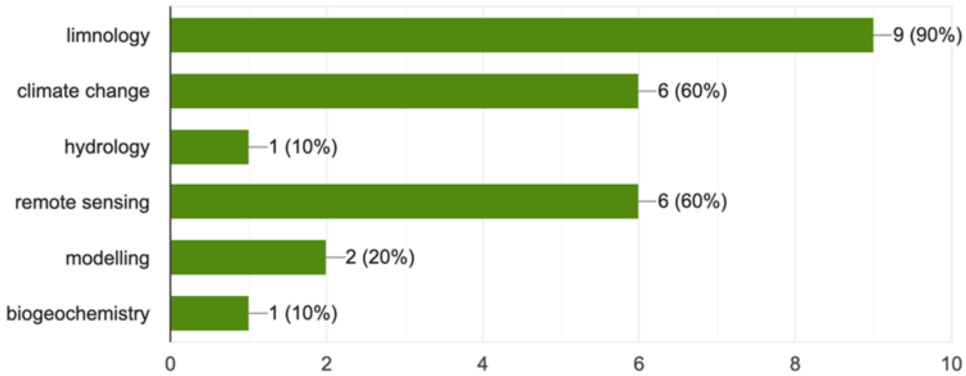


5. How would you prefer the water transparency data to be aggregated? [for each category indicate how useful this would be, where 1 = not at all useful, 5 = extremely useful]



6. What's your study field? [multiple answers allowed]

10 responses



7. Please provide any further recommendations/suggestions below:

2 responses

thanks for your work

I think this would be a very valuable product; global modelling efforts now have to estimate water transparency with very simplified relationships, which can cause very large errors, even for water temperature, let alone biogeochemical variables. Even if these remotely-sensed estimates have a considerable error margin, it would still improve global modelling results a lot.

In the synthesis, the Secchi depth is actually preferred to the Kd value. But looking at the comments, it seems that Kd is more useful for modellers, but Secchi depth is more diffuse in limnological studies and in situ measurements. Kd values are requested as a single value integrated over the PAR or as multiple values for all possible wavelengths. For data aggregation, a per pixel value and a daily resolution are considered very useful, together with a per lake time series format (a NetCDF file).

4.4 Other feedback

During the 2023 Annual Meeting of the Lakes_cci project, we invited a scientist who experienced the use of the Lakes ECVs. This scientist judged the overall quality of the Lakes_cci dataset to be good, and we collected the following bullet points of feedback/needs.

- Datasets are too large to handle for many limnologists
- A per-lake spatially resolved data product would be useful
- Gaps in the data are always an issue; would a gap filled product be possible?
- A global lake mean (lake centre) data product
- Inconsistency in number of variables in the files (this may now have been resolved)
- Critical to keep this going; 30 years dataset for Lake ECVs

Actually, for the first two points, some of the ways to extract data for a specific lake or region are offered in GitHub tools (https://github.com/cci-lakes/lakes_cci_tools), where a set of Python scripts and a Jupiter notebook are provided. A gap filling is planned for LSWT and ice cover data in the next release. The inconsistencies are now fixed, or at least we have not received any more feedback on them. Another step was the removal of inconsistencies between LSWT, LIC and chlorophyll-a and turbidity data (derived from LWLR). The final point on long-term continuity may be taken up in discussions regarding the regrouping of ECV Products by GCOS.

4.5 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.

As part of a final contract extension in the current project phase, interaction with GLEON takes shape in the form of its lake physical modelling group (where addition of K_d will likely prompt more uptake) and the working group looking at the occurrence of cyanobacteria and cyanobacteria blooms. The latter part will be supported by a stand-alone data sets applying cyanobacteria pigment indicator algorithms to the Lake Colour dataset.

Figure 17. Geo AquaWatch home page with the announcement of the Lakes_cci survey.

A direct contact with the GLEON network was established in 2022, and one Science Lead of the Lakes_cci and I. Woolway have participated in the pertinent working group established 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.

During the 2023 Annual meeting some potential synergies with the GLEON community were reported by the Science leaders of the Lakes_cci project and are summarised in Table 13.

Table 13. Potential synergies with GLEON.

Argument	Theme
Processes/mechanisms	Exploring SWOT to study cyclonic upwelling in large lakes River/stream intrusion into lakes – variable intrusion depth effects on mixing and biology

	Demonstrate intrusion extent at surface with RS Validate Kd(PAR)
Model assimilation	Elucidate observability of deep chlorophyll maxima Elucidate link between surface water heat trapping and light extinction coefficient
Trends/hotspots	Multi-decadal trends in cyanobacteria from remote sensing

An update on the external conference attended by the consortium is given below (Table 14). This activity provided an opportunity to disseminate information on the use of the dataset (v2.0.2) and the availability of the new version 2.1, which covers more than 2000 lakes until 2022.

Table 14 List of conference, with dates, partners and type of contribution, attended by Lakes_cci consortium in the period November 2022 to October 2024.

Event name	Type (workshop, conf, etc.)	Dates	Location	Who attend?	Presentation /poster / chair	Title
EGU 2023	Conference	23–28 April 2023	Vienna, Austria	H2O, CLS	Presentation	Demonstration of the Lakes_cci dataset; LSC presentation
AI4Copernicus 2023, Earth Observation & Artificial Intelligence Solutions for Climate Change Challenges	Symposium	23-May-23	Luxembourg	SERTIT	Poster	Water boody detection and extraction with Multi Layer Perceptron, GSW and Sentinel 2 time series
11th Shallow lakes Conference	Conference	11-16 June 2023	Tartu, Estonia	CNR	Poster	Analysis of time series of the Essential Climate Variables of shallow lakes from Lakes_CCI dataset
Physical processes in natural waters (PPNW)	Conference	19-23 June 2023	Brescia, Italy	CNR	Presentation	Two presentations Lakes_cci presentation;
Global Lakes Ecological Observation Network - GLEON 2023 All Hands	Workshop	23-30 June 2023	Ryn, Poland	PML, CNR	Presentation/Poster	3-hr workshop in collaboration with Water-ForCE, remote sensing theory + exploring Lakes_cci dataset
GCOS meeting	Meeting	24-30 June 2023	Bonn, Germany	LEGOS	Presentation	Lakes_cci presentation
ASLO 2023	Conference	4–9 June 2023	Palma de Mallorca, Spain	CNR, H2O, UoS	Chair/presentations	SS055 Remote Sensing of Freshwaters Health from Local to Global Scales Under Climate Change; Integration of multi-source remote sensing data to investigate lake ecological responses to climate change; Recent Global Trends and variability in Lake ice cover documented from satellite observations; Remote sensing observed impacts of La Niña on water quantity and quality in Lake Qadisiyah, Iraq

EARSEL 2023	Conference	3-6 July 2023	Bucharest, Romania	CNR	Presentation	The impact of wildfires on water quality using CCI EO products: the Lake Baikal case study
DASIF final meeitng	Project meeting	30 Aug 2023	Berlin, Germany	BC	Presentation	Transfer of climate indicators to global application
Symposium WCPR Open Science	Conference	23-27 Oct 2023	Kigali, Rwanda	LEGOS/CNES	Presentation/Poster	Consolidation of datasets of Essential Climate Variables: case of the Lake Water Extent exploiting HR imagery and Altimetry times series within the ESA CCI Lakes Framework; cases African lakes; Impact on lake surface water quality of heatwaves and burning events in the lakes watershed
Symposium WCPR Open Science	Conference	23-27 Oct 2023	Kigali, Rwanda	LEGOS/CNES	Presentation	Long and short term of Fitri lake (Chad) monitoring based on HR satellite imagery: an unique source of information for the lake study and management,
13th CCI Colocation and CMUG Integration meeting	Meeting	7-9 Nov 2023	ECSAT	CNR, CLS, UoR	Poster	CCI ECV Lakes: satellite-derived lakes variables exploration & new insights; LSC option
HYDROSPACE	Workshop	27-30 Nov 2023	Lisbon, Portugal	LEGOS/CLS/H20	Poster/Presentation	Lakes_cci project and dataset; LSC option; Improving the LIT estimation with high resolution radar altimetry data
HYDROLARE	Conference	8 Nov 2023	Online	CNES	Presentation	Lakes_cci project: Essential climate Variables on lakes from remote sensing, an overview of the challenges, objectives and current realization from the CCI program of ESA
IOCS 2023	Conference	14-17 Nov 2023	St. Petersburg, Florida, USA	CNR	Poster	Exploring the satellite-derived lakes variables for climate studies
SIL Congress 2024	Conference	05-09 May 2024	Foz do Iguacu, Brasil	CNR	Presentation	Exploration of satellite-derived climate essential lakes variables in South American and African lakes
EARSEL Valencia	Conference	16-18 April 2024	Valencia, Spain	CNR	Presentation	Assessment of the influence of wildfires on water quality of lakes in ESA CCI global datasets by deep learning
EGU 2024	Conference	14-19 April 2024	Vienna	CNR	Presentation/Poster	Lakes act as slow integrators of atmospheric disturbance like oceans: Evidences from a deep perialpline lake; A global dataset for lake physical variables from satellite measurements
AIOL 2024	Conference	24-28 June 2024	Lecco, Italy	CNR	Presentation	Examining global trends in shallow lakes using satellite derived data from the Climate Change Initiative Lakes_cci project
PPNW2024	Conference	1-5 July 2024	Girona, Spain	CNR, PML, UoR	Chair/Presentation	Subworkshop-Remote Sensing in Lakes; Lakes_cci project and dataset presentation; Global lake surface water temperature and ice cover for climate related applications; Sentinel Lakes of sub-Sahelian Africa: An

						assessment based on multivariate remote sensing and modeling data
IGARSS 2024	Conference	7-12 July 2024	Athens, Greece	CNR	Presentation	Exploring the satellite-derived lakes variables for climate studies
Unlocking the Global Benefits of Water Quality Monitoring through Earth Observation	Workshop	28-30 August 2024	Stirling, UK	UoS, PML	Discussion, presentation	Impacts of climate and human activities on water quantity and quality in lakes: satellite observation.
EARSEL: Remote Sensing of Forest Fires: Lessons learned and future challenges under a changing climate	Conference	19-20 September 2024	Milan, Italy	CNR	Poster	Assessing the impact of wildfires on lake water quality worldwide from satellite data
EO4AFRICA	Conference	23-26 September 2024	Rome, Italy	CNR	Presentation	Assessment of water quality changes in African lakes in response to climate trends and extreme events using satellite and meteo-climatic data
International Conference for YOUNG Marine Researchers – ICYMARE	Conference	16-20 September 2024	Bremen, Germany	CNR	Presentation	Monitoring water quality of Sub-Sahelian African lakes using satellite data: Comparing the effects of extreme weather events on inland and coastal waterbodies
International Conference for YOUNG Marine Researchers – ICYMARE	Conference	16-20 September 2024	Bremen, Germany	CNR	Poster	From Space to Coast: Exploiting Satellite-Derived Water Quality Variables for Climate Studies
Ocean Optics XXVI	Conference	6-11 Oct 2024	Las Palmas de Gran Canaria, Spain	UoS, PML, CNR	Presentation	Developing a global optical water type classification-based framework to estimate coloured dissolved organic matter(CDOM) for lakes.
14th CCI Colocation and CMUG Integration meeting	Meeting	16-18 Oct 2024	ECSAT	CNR	Poster	Lakes: new insights and products
7th LAKES 2024 Workshop on Parameterisation of Lakes in Numerical Weather Prediction and Climate Modelling	Workshop	20-22 Nov 2024	Milan, Italy	CNR, UoR, H2O Geomatics/University of Waterloo	Presentations and Posters	PRESENTATIONS: i. Towards the Development of Global Gap-Filled Lake Surface Water Temperature and Ice Cover Products; ii. Lake-climate interactions in African sub-Sahelian lakes: a continental-scale assessment based on multivariate remote sensing and modeling data. POSTERS: i. Overview of the ESA Lakes Climate Change Initiative; ii. New insights from the Lakes_cci project on satellite-derived lake variables for climate studies

The list of “internal” papers published in 2023 and 2024 by the partners of the Consortium using the Lake_cci dataset for the years 2023 and 2024 (December) is reported in Table 15.

Table 15 List of publications produced by the Lakes_cci Consortium using the Lakes ECVs in the period January 2023 to December 2024.

Publications
2024
1. Impacts of droughts and human activities on water quantity and quality: Remote sensing observations of Lake Qadisiyah, Iraq. **Dalin Jiang**, Ian Jones, **Xiaohan Liu**, **Stefan G.H. Simis**, **Jean-François Cretaux**, **Clement Albergel**, Andrew Tyler, **Evangelos Spyrakos.** International Journal of Applied Earth Observation and Geoinformation, Volume 132, 2024, 104021, ISSN 1569-8432. https://doi.org/10.1016/j.jag.2024.104021
2. Strengthening of the hydrological cycle in the Lake Chad Basin under current climate change. F. Sylvestre, A. Mahamat-Nour, T. Naradoum, M. Alcoba, L. Gal, A. Paris, **J-F. Cretaux**, B. Pham-Duc, M. Mahamat Ahmat, D. Gaya. *Nat. Geosci.* **17**, 516–523 (2024). https://doi.org/10.1038/s41561-024-01446-w
3. Prospects of Using Satellite Data for Determining Water Levels in Large Lakes and Reservoirs: A Case Study for Russian Water Bodies. Vuglinskii, V.S., **Cretaux, J.F.**, Izmailova, A.V. *et al. Russ. Meteorol. Hydrol.* **49**, 1–8 (2024) https://doi.org/10.3103/S1068373924010011
4. Lake-TopoCat: A global lake drainage topology and catchment dataset. Sikder, M. S., Wang, J., Allen, G. H., Sheng, Y., Yamazaki, D., Song, C., Ding, M., Crétaux, J.-F., and Pavelsky, T. M., 2023. *Earth System Science Data*, 15, 3483-3511, https://doi.org/10.5194/essd-15-3483-2023
5. Slow response of surface water temperature to fast atmospheric variability reveals mixing heterogeneity in a deep lake. **Amadori, M., Bresciani, M., Giardino, C. et al.** Sci Rep 14, 8459 (2024). https://doi.org/10.1038/s41598-024-58547-0
6. Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. Piccolroaz, S., Zhu, S., Ladwig, R.,**Carrea, L.**, Oliver, S., Piotrowski, A. P.,et al. (2024). Reviews of Geophysics,62, e2023RG000816. https://doi.org/10.1029/2023RG000816
7. Surface water temperature observations and ice phenology estimations for 1.4 million lakes globally. Maartje C. Korver, Bernhard Lehner, Jeffrey A. Cardille, **Laura Carrea**, Remote Sensing of Environment, Volume 308,2024,114164,ISSN 0034-4257, https://doi.org/10.1016/j.rse.2024.114164.
8. Challenges and prospects for modeling lake water temperature in a changing climate Piccolroaz, S., S. Zhu, R. Ladwig, **L. Carrea,** S. Oliver, A. P. Piotrowski, M. Ptak, R. Shinohara, M. Sojka, R. **I. Woolway**, and D. Z. Zhu (2024),, Eos, 105, https://doi.org/10.1029/2024EO245013. Published on 1st March
9. Quantifying decadal stability of lake reflectance and chlorophyll-*a* from medium-resolution ocean color sensors. **Xiaohan Liu, Mark Warren, Nick Selmes, Stefan G.H. Simis.** Remote Sensing of Environment, Volume 306, 2024, 114120, ISSN 0034-4257. https://doi.org/10.1016/j.rse.2024.114120.
10. Investigating the Impact of Wildfires on Lake Water Quality Using Earth Observation Satellites. **Caroni, R.; Pinardi, M.**; Free, G.; **Stroppiana, D.**; Parigi, L.; Tellina, G.; **Bresciani, M.**; **Albergel, C.; Giardino, C**. *Appl. Sci.* **2024**, *14*, 2626. https://doi.org/10.3390/app14062626
11. Detecting climate-related shifts in lakes: A review of the use of satellite Earth Observation. Calamita, E., Lever, J.J., **Albergel, C.**, **Woolway, R.I**. and Odermatt, D. (2024) Limnol Oceanography, https://doi.org/10.1002/lno.12498
12. Lake Tanganyika basin water storage variations analysis over 2003-2021 for water balance monitoring and flood study. **Gbetkom P., Cretaux J-F.**, Biancamaria S, Blazquez A, Gosset M, Paris A, Tchilibou M, Laetitia Gal L, Kitambo B, Jucá Oliveira R-A. 2024, *Remote Sensing Applications: Society and Environment*, 34, 101182, ISSN 2352-9385, https://doi.org/10.1016/j.rsase.2024.101182.
13. Improving the Estimation of Lake Ice Thickness with High-Resolution Radar Altimetry Data. **Mangilli, A.; Duguay, C.R.; Murfitt, J.**; Moreau, T.; Amraoui, S.; **Mugunthan, J.S.**; Thibaut, P.; Donlon, C. *Remote Sens.* 2024, *16*, 2510. https://doi.org/10.3390/rs16142510.
14. Lake surface water temperature [in State of the Climate Report] in Bulletins of the American Meteorological Society. **Carrea, L., C.J. Merchant, R.I. Woolway** et al (2024), 105 (8), S33-S35, https://doi.org/10.1175/BAMS-D-24-0116.1
15. Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. S. Piccolroaz, S. Zhu, R. Ladwig, **L. Carrea**, S. Oliver, A. P. Piotrowski, M. Ptak, R. Shinohara, M. Sojka, R. I. Woolway, D. Z. Zhu. Reviews of Geophysics. https://doi.org/10.1029/2023RG000816

2023	
1.	Assessing the impact of wildfires on water quality using satellite remote sensing: the Lake Baikal case study. **Pinardi M, Stroppiana D, Caroni R, Parigi L, Tellina G, Free G, Giardino C, Albergel C and Bresciani M** (2023) *Front. Remote Sens.* 4:1107275. doi: 10.3389/frsen.2023.1107275
2.	Satellites reveal widespread decline in global lake water storage. Fangfant Yao, Ben Livneh, Balaji Rajagopalan , Jida Wang, **Jean-François Crétaux**, Yoshihide Wada and Muriel **Bergé-Nguyen**. *Science*380,743-749(2023).DOI:10.1126/science.abo2812
3.	Satellite-derived multivariate world-wide lake physical variable timeseries for climate studies. **Laura Carrea, Jean-François Crétaux, Xiaohan Liu, Yuhao Wu, Beatriz Calmettes, Claude R. Duguay, Christopher J. Merchant, Nick Selmes, Stefan G. H. Simis, Mark Warren, Hervé Yesou, Dagmar Müller, Dalin Jiang, Owen Embury, Muriel Bergé-Nguyen & Clément Albergel** . *Sci Data* **10**, 30 (2023). https://doi.org/10.1038/s41597-022-01889-z
4.	Lake Chad vegetation cover and surface water variations in response to rainfall fluctuations under recent climate conditions (2000–2020). **Paul Gérard Gbetkom, Jean-François Crétaux**, Michel Tchilibou, Alice Carret, Manon Delhoume, **Muriel Bergé-Nguyen**, Florence Sylvestre. Science of The Total Environment, 2023. https://doi.org/10.1016/j.scitotenv.2022.159302
5.	A data-driven approach to flag land-affected signals in satellite derived water quality from small lakes. **DalinJiang, JorritScholze, XiaohanLiu, Stefan G.H.Simis, KerstinStelzer, DagmarMüller, PeterHunter, AndrewTyler, EvangelosSpyrakos**. International Journal of Applied Earth Observation and Geoinformation, Volume 117, 2023, 103188, ISSN 1569-8432, https://doi.org/10.1016/j.jag.2023.103188.
6.	Comparison and correction of satellite measurements using in-situ observations of lake surface heights: A case study in lake Baikal. V.S. Vuglinsky, **J-F Cretaux**, A.V. Izmailova, S.I. Gusev, M. Berge-Nguyen, **B. Calmettes**. Advances in Space Research, Volume 71, Issue 10, 2023, Pages 4030-4044, ISSN 0273-1177, https://doi.org/10.1016/j.asr.2022.12.046.
7.	Inland Surface Waters Quantity Monitored from Remote Sensing. **Cretaux, JF.**, Calmant, S., Papa, F. *et al. Surv Geophys* **44**, 1519–1552 (2023). https://doi.org/10.1007/s10712-023-09803-x
8.	Machine learning based classification of lake ice and open water from Sentinel-3 SAR altimetry waveforms. **Jaya Sree Mugunthan, Claude R. Duguay, Elena Zakharova.** Remote Sensing of Environment, Volume 299, 2023, 113891, ISSN 0034-4257, https://doi.org/10.1016/j.rse.2023.113891

4.6 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 URD-V1.1 (Dec. 2022; Phase 2).

In order to update the overview of the topic, we again performed a Scopus search with the keywords "satellite" + "global lakes" + "climate change" for the period from 2015 to the present (December 2024). A total of 1537 documents (limited to articles and reviews) were found, with a sharp increase since 2020 (Figure 18).

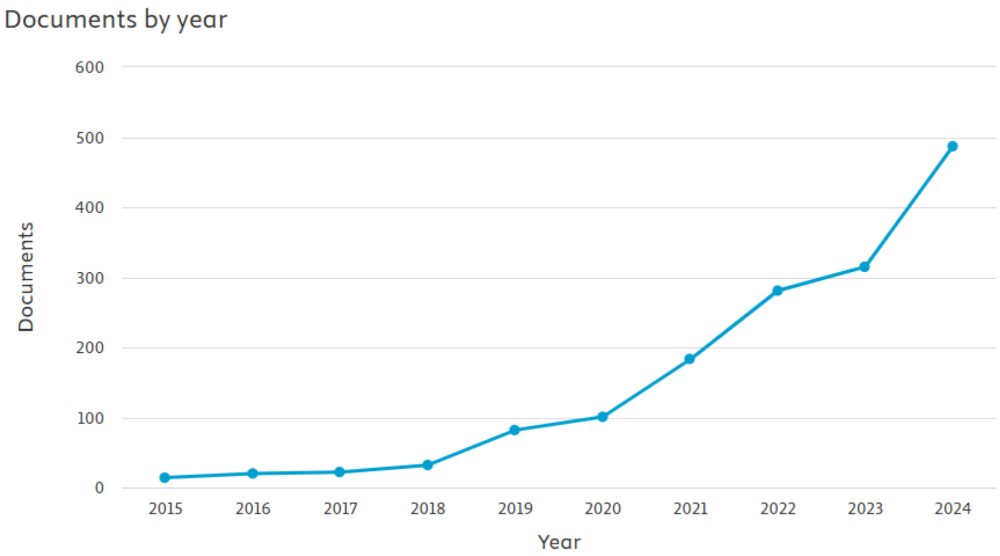


Figure 18. Published papers per year returned from Scopus search queries "satellite"+ "global lakes" + "climate change" from 2015 to December 2024.

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 Canada.

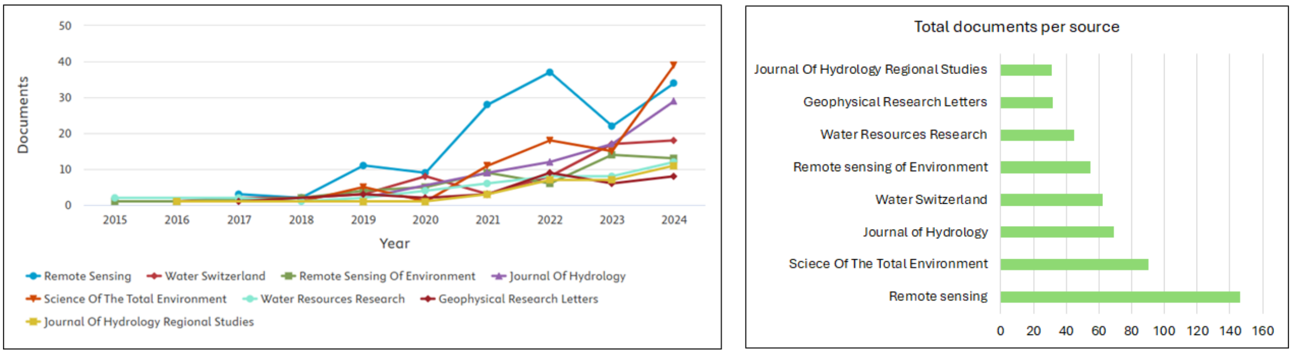


Figure 19. Documents per year by source (first ten sources; on the left), and total documents per source (including sources with at least 30 publications). Period 2015 – December 2024. Source: Scopus search.

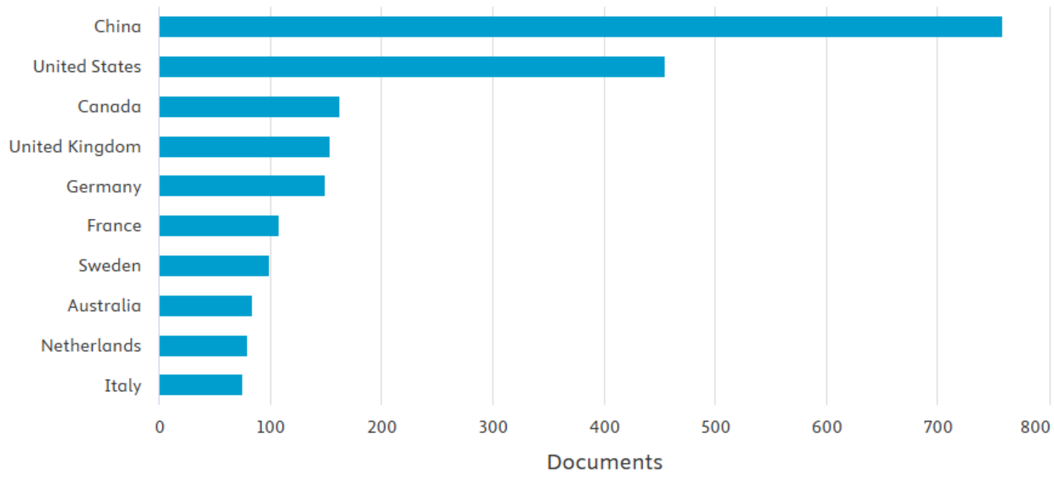
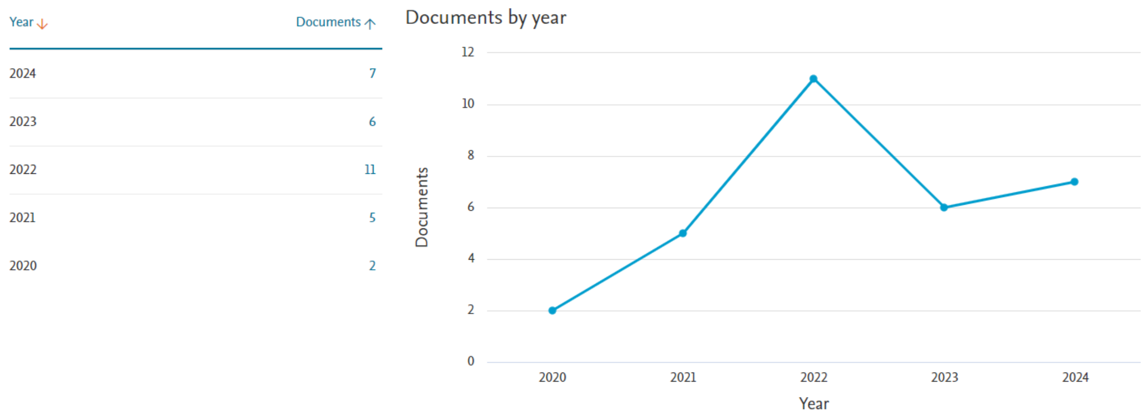


Figure 20. Distribution of publications by country/territory returned from Scopus query for the period 2015-2024.

4.6.1 External Studies

In the document released last December 2023 (Climate Assessment Report) we reported a preliminary overview of external scientific studies including or based on the Lakes_cci ECVs dataset. In this section, Figure 21 shows a graph of the published papers per year returned by the Scopus search queries "Lakes cci", with a total of 35 papers (2020-2024). Table 16 shows the list of publications by other authors not directly involved in the Lakes_cci project.



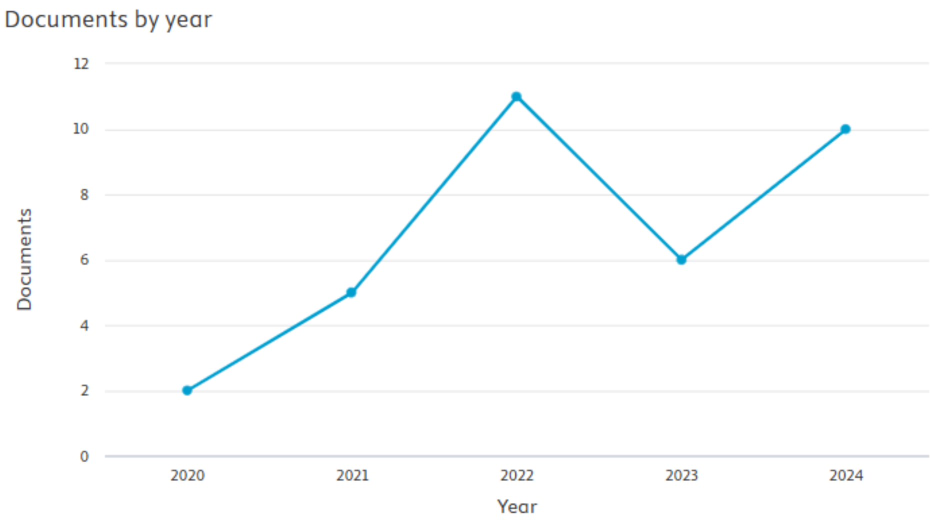


Figure 21. Published papers per year returned from Scopus search queries "Lakes cci" from 2020 to December 2024.

Table 16 List of external studies based on Lakes_cci ECVs dataset.

Authors, Year, Title, Journal	Contents, variables
Tigli, M., Bak, M. P., Janse, J. H., Strokal, M., & Janssen, A. B. (2025). The future of algal blooms in lakes globally is in our hands. *Water Research*, *268*, 122533.	This study examines future trends in algal blooms in lakes globally for >3500 'representative lakes' for the year 2050, considering the attribution of both nutrient and climate factors. A soft-coupled process-based lake ecosystem model (PCLake+) with a watershed nutrient model (MARINA-Multi) was used to assess trends in algal blooms in using the Trophic State Index for chlorophyll-a (TSI-Chla). To evaluate the baseline of the model, the results were compared with two global datasets, one of satellite-derived chlorophyll-a values (from Lakes_cci; Carrea et al., 2023) and one of measured chlorophyll-a concentrations (Filazzola et al., 2020). When the outliers are excluded, the mean lower and upper quartiles of the two datasets are slightly higher, but the authors believe that the estimates of their model are consistent with the results of these two other studies.
Baltodano, A., Agramont, A., Lekarkar, K., Spyrakos, E., Reusen, I., & van Griensven, A. (2024). Exploring global remote sensing products for water quality assessment: Lake Nicaragua case study. *Remote Sensing Applications: Society and Environment*, *36*, 101331.	This study explores the applicability of 13 globally-derived Chlorophyll-a (CHL) products from optical satellite remote sensing to support local water quality management in Lake Nicaragua. The temporal and spatial consistency between the products was analyzed, as well as their agreement with in-situ data collected from 2011 to 2016. The Climate Change Initiative (CCI) CHL product was identified as the most stable and reliable, suggesting its suitability for monitoring Lake Nicaragua. However, the correlation of this product with in-situ measurements was weak.
Wang, X., Shi, K., Zhang, Y., Qin, B., Zhang, Y., Wang, W., ... & Jeppesen, E. (2023). Climate change drives rapid warming and increasing heatwaves of lakes. Science bulletin, 68(14), 1574-1584.	To improve lake temperature modelling and to investigate the complexities of surface water temperature trends and heatwaves occurrence in Chinese lakes from 1980 to 2100, Wang et al. (2023) combined satellite measurements with a numerical model. Climate forcing from ERA5-Land were used to drive the FLake model during historic period, and the model has been fine-tuned using the Lakes_cci LSWT data, resulting in a projection of future change.
Cazzaniga, I., Zibordi, G., Alikas, K., & Kratzer, S. (2023). Temporal changes in the remote sensing reflectance at Lake	Satellite-derived LSWT, Chl-a and turbidity products from the CCI Lakes dataset were considered in addition to MODIS-A data. After evaluating their accuracy against in situ data, which gave good fit results, it was possible to use these products in the subsequent study. Specifically,

Vänern. Journal of Great Lakes Research, 49(2), 357-367.	only pixels marked as "best quality data" were included in the average of 3 x 3 pixels (i.e. ~ 9 km^2) centered on the in situ stations.
Calamita, E., Brechbühler, M., Woolway, I., Albergel, C., & Odermatt, D. (2023, May). Detecting lake mixing anomalies using Earth Observation. In EGU General Assembly Conference Abstracts (pp. EGU-15065).	The Lakes_cci LSWT dataset was taken into on the identification of lake mixing anomalies. Long-term lake warming is frequently illustrated in terms of spatial averages using remotely detected lake surface water temperatures. The objective of this study was to evaluate the long-term variability in the mixing of large lakes in the context of climate change. To that end, the horizontal data gradients were utilized to better understand internal dynamics of lakes and to identify lake mixing anomalies. The authors employed a method known as 'thermal front tracking', which is far more common in oceanography than in limnology, to find mixing anomalies in dimictic lakes throughout the globe.
Zhao, D., Huang, J., Li, Z., Yu, G., & Shen, H. (2024). Dynamic monitoring and analysis of chlorophyll-a concentrations in global lakes using Sentinel-2 images in Google Earth Engine. Science of The Total Environment, 912, 169152.	Mean Chl-a concentration was estimated for 3067 globally distributed lakes for the period 2019-2021 by applying different algorithms to Sentinel-2 images based on Optical Water Type classification using GEE. Lakes_cci Chl-a data were used as auxiliary data and Chl-a monthly average was chosen to validate the retrieved Chl-a in this study.
Bonnier, M., Anneville, O., Woolway, R. I., Thackeray, S. J., Morin, G. P., Reynaud, N., ... & Harmel, T. (2024). Assessing ESA Climate Change Initiative data for the monitoring of phytoplankton abundance and phenology in deep lakes: Investigation on Lake Geneva. *Journal of Great Lakes Research*, 102372.	In this tudy, the Lakes_cci Chl-a dataset was analyzed to assess its representativeness for water quality monitoring and subsequent phenology studies in Lake Geneva. The dataset was evaluated through match-up comparisons. A specific analysis was performed to evaluate any potential biases in remote sensing estimation, and consequences for observed phenological trends, as the underlying algorithms do not take into account the vertical distribution of phytoplankton. Different approaches to data averaging were performed to reconstruct Chl-a estimates provided by the remote sensing algorithms. Strong correlation (R-value > 0.89) and acceptable discrepancies (rmse ~ 1.4 mg m^{-3}) were observed for the Lakes_cci data. This approach permitted recalibration of this data for Lake Geneva. Finally, the authors merged satellite and in-situ data to provide a consistent time series for long term analysis of phytoplankton phenology and its interannual variability since 2002.
Kangro, K., Pall, A. M., Laugaste, R., Piirsoo, K., Maileht, K., Rahn, I. A., & Alikas, K. (2024). Two decades of cyanobacterial bloom dynamics in a shallow eutrophic lake: remote sensing methods in combination with light microscopy. *Hydrobiologia*, 1-18.	Remote sensing methods were used to characterizespatial and temporal bloom dynamics in three parts of Lake Peipsi over two decades. LSWT and LWL data from Lakes_cci project for Lake Peipsi were used to calculate the long-term average of the period 1995–2020. Then the authors calculated the differences in LSWT and LWL from the long-term average for specific days in the period of 2004–2020. The water level in combination with the water temperature helps to explain the changes in phytoplankton biomass and bloom parameters.
Tong, J., Gao, Y., Zhan, P., Song, C. (2024). Advances in lake ice monitoring methods based on remote sensing technology. National Remote Sensing Bulletin, 28 (3)541-557 (DOI : 10.11834/jrs.20232447) (in Chinese)	This study presents a review on the remote sensing data source and methods for lake ice studies as well as spatial and temporal variations of lake ice in global hotspots. The commonly used remote sensing data sources for lake ice monitoring, which include spaceborne and airborne remote sensing platforms and existing lake ice data products were reviewed. LIC product by Lakes_cci project is reported in the study. This review likewise summaries the research hotspots of lake ice which are mostly distributed in the Northern hemisphere, especially in Northern Europe, North America, and the Tibetan Plateau and analyzes the spatial and temporal characteristics of lake ice variations.
Tang, F., Chen, P., An, Z., Xiong, M., Chen, H., & Qiu, L. (2023). A Dual-Threshold Algorithm for Ice-Covered Lake Water Level Retrieval Using	In this study, the Lakes_cci dataset is cite in the introduction of the paper which propose a modified method to determine the current surface type of lakes, analyzing changes in backscattering coefficients and brightness temperature using Sentinel-3 SAR Altimetry.

Sentinel-3 SAR Altimetry Waveforms. Sensors, 23(24), 9724.	
Giroux-Bougard, X., Fluet-Chouinard, E., Crowley, M. A., Cardille, J. A., & Humphries, M. M. (2023). Multi-sensor detection of spring breakup phenology of Canada's lakes. Remote Sensing of Environment, 295, 113656.	In this study, the authors detected the sequence of transition from ice to water in each pixel's time series to estimate the occurrence of breakup each year. They deployed the OPEN-ICE algorithm over all freshwater pixels of Canada for the period of 2013 to 2021. In the paper the Lakes_cci LIC dataset was cited in the list of currently available large-scale data products used for monitoring sea ice, snow cover, and lake ice.
Li, X., Peng, S., Xi, Y., Woolway, R. I., & Liu, G. (2022). Earlier ice loss accelerates lake warming in the Northern Hemisphere. *Nature communications*, *13*(1), 5156.	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. 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. In this paper the LSWT product (v1) was used to validate the results from ERA5.
Maxant, J., Braun, R., Caspard, M., & Clandillon, S. (2022). ExtractEO, a Pipeline for Disaster Extent Mapping in the Context of Emergency Management. Remote Sensing, 14(20), 5253.	In the context of emergency management this study explore a pipeline for Disaster Extent Mapping. An automated flood and fire extraction Pipelines (ExtractEO) is presented, making it possible to take full advantage of advanced algorithms in short timeframes, and leave enough time for an expert operator to validate the results and correct errors. In the paper the Lakes ECVs are cited, and in particular LWE (e.g. Lake Fitri LWE curve derived from Sentinel-2 data from 2017 to 2021 is also shown).
Clason, C., Rangecroft, S., Owens, P. N., Łokas, E., Baccolo, G., Selmes, N., ... & Blake, W. (2022). Contribution of glaciers to water, energy and food security in mountain regions: current perspectives and future priorities. Annals of Glaciology, 63(87-89), 73-78.	This paper consider the socio-environmental role of and pressures on glacier-fed waters, discuss key research priorities for the assessment of both the quantity and quality of meltwater and reflect on the importance of a transdisciplinary and inclusive research landscape. In this study the Lakes_cci dataset is cited as an example of how freshwater bodies can now be routinely monitored for water quality, water temperature and spatial extent.
Tom, M., Wu, T., Baltsavias, E., & Schindler, K. (2022). Recent ice trends in Swiss mountain lakes: 20-year analysis of MODIS imagery. PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science, 90(4), 413-431.	This study observe the Lake Ice Phenology events, such as freeze-up, break-up and ice cover duration, across two decades (2000–2020) from optical satellite images in small- and medium-sized mountain lakes in Switzerland. In the introduction the LIC dataset (from Lakes_cci) is cited as the only operational lake ice product available, but the target lakes of this study were not included among the 250 lakes (v1).
Pickens, A. H., Hansen, M. C., Stehman, S. V., Tyukavina, A., Potapov, P., Zalles, V., & Higgins, J. (2022). Global seasonal dynamics of inland open water and ice. Remote Sensing of Environment, 272, 112963.	In this study a first monthly global area estimates of open water and ice with uncertainty bounds was estimated. In the introduction, the opportunity to monitor different Lakes ECVs for 253 lakes around the world from Lakes_cci dataset is reported. The output maps reveal the high spatiotemporal variability of ice phenology, thanks to the near-daily observations near the poles and the 10 m resolution bands of Sentinel-2.
Feng, Y., Zhang, H., Tao, S., Ao, Z., Song, C., Chave, J., ... & Fang, J. (2022). Decadal lake volume changes (2003–2020) and driving forces at a global scale. Remote Sensing, 14(4), 1032.	This study used Lakes_cci dataset (i.e. LWL) and in situ measurements to validate the estimated water levels and volumes. The comparison of water levels retrieved from ICESat/ICESat-2 with Lakes_cci products. This latter shown a lower accuracy compared to the performance of ICESat/ICESat-2 (NRMSE of 22% vs 0.5%).
Zeng, C., & Binding, C. E. (2021). Consistent multi-mission measures of inland water algal bloom spatial extent using MERIS, MODIS and OLCI. Remote Sensing, 13(17), 3349.	This study aimed to address the gap in spectral resolution and product continuity between sensors (MERIS and OLCI) by developing a Neural Network (NN) approach to build spectral band consistency between sensors (MODIS and the MERIS/OLCI) in order to provide continuous algal bloom products. The Lakes_cci project and its aim to create a

	consistent and homogenous data set of lake products for the Lakes Essential Climate Variable is cited in the introduction of this paper.
Zhao, N., Fan, Z., & Zhao, M. (2021). A new approach for estimating dissolved oxygen based on a high-accuracy surface modeling method. Sensors, 21(12), 3954.	This study proposed a new approach for estimating the spatial distribution of DO concentrations with respect to explanatory variables in Poyang Lake, China. LSWT from Lakes_cci was used in this study as input dataset.
Woolway, R. I., & Maberly, S. C. (2020). Climate velocity in inland standing waters. Nature Climate Change, 10(12), 1124-1129.	In this study, the velocity of climate change in inland standing waters from 1979 to 2018 with those calculated for marine and terrestrial ecosystems by applying the same climate velocity algorithm to surface air temperatures over land and sea surface temperatures. In this study, the lake surface temperatures from ERA5 were validated with satellite-derived LSWT from Lakes_cci project. A good agreement was obtained between the simulations and satellite-derived observations of lake surface temperature.

4.7 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 still remain the main requirements, which will be addressed with the V3.0 of the dataset for these two ECVs…. 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).

From the experience of the two user workshops, the community of physical limnologists is still far from routinely using remote sensing data, but there is a growing interest, attracted by high quality LSWT, LWL, LIC and water quality products with high spatial resolution suitable for per lake analysis. While the NWP and climate modelling community appreciated the ongoing work on the retrieval of water transparency for lakes at global level.

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, the user workshops feedback, 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. Part of the response to this challenge could come from the Lake Storage Change Option. 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, extinction coefficient, and lake storage change. 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 coming months, a wider scientific community is expected to be reached, thanks to the improvements of the latest version of the dataset (v2.1), such as global spatial coverage for all variables, and the recent interaction at the CMUG and Colocation meeting and with the GLEON network (Lakes_cci working group). In the latter context, a link to ISIMIP can be crucial and has been established with the Lakes Workshop in November 2024..

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.

6 References

Allen, G.H. and T.M. Pavelsky, 2018: Global extent of rivers and streams. Science, 361(6402), 585–588, doi:10.1126/science.aat0636

Baltodano, A., Agramont, A., Lekarkar, K., Spyrakos, E., Reusen, I., & van Griensven, A. (2024). Exploring global remote sensing products for water quality assessment: Lake Nicaragua case study. *Remote Sensing Applications: Society and Environment*, *36*, 101331.

Bonnier, M., Anneville, O., Woolway, R. I., Thackeray, S. J., Morin, G. P., Reynaud, N., ... & Harmel, T. (2024). Assessing ESA Climate Change Initiative data for the monitoring of phytoplankton abundance and phenology in deep lakes: Investigation on Lake Geneva. Journal of Great Lakes Research, 102372

Calamita, E., Brechbühler, M., Woolway, I., Albergel, C., & Odermatt, D. (2023, May). Detecting lake mixing anomalies using Earth Observation. In EGU General Assembly Conference Abstracts (pp. EGU-15065).

Cazzaniga, I., Zibordi, G., Alikas, K., & Kratzer, S. (2023). Temporal changes in the remote sensing reflectance at Lake Vänern. Journal of Great Lakes Research, 49(2), 357-367.

Clason, C., Rangecroft, S., Owens, P. N., Łokas, E., Baccolo, G., Selmes, N., ... & Blake, W. (2022). Contribution of glaciers to water, energy and food security in mountain regions: current perspectives and future priorities. Annals of Glaciology, 63(87-89), 73-78.

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

Colonia, D. et al., 2017: Compiling an Inventory of Glacier-Bed Overdeepenings and Potential New Lakes in De-Glaciating Areas of the Peruvian Andes: Approach, First Results, and Perspectives for Adaptation to Climate Change. Water, 9(5), 336, doi:10.3390/w9050336.

Feng, Y., Zhang, H., Tao, S., Ao, Z., Song, C., Chave, J., ... & Fang, J. (2022). Decadal lake volume changes (2003–2020) and driving forces at a global scale. Remote Sensing, 14(4), 1032.

Giroux-Bougard, X., Fluet-Chouinard, E., Crowley, M. A., Cardille, J. A., & Humphries, M. M. (2023). Multi-sensor detection of spring breakup phenology of Canada's lakes. Remote Sensing of Environment, 295, 113656.

Global Climate Observing System programme (GCOS), (GCOS 244), 2022a. The GCOS 2022 Implementation Plan. https://library.wmo.int/index.php?lvl=notice_display&id=22134

Global Climate Observing System programme (GCOS), (GCOS 245), 2022b. The 2022 ECVs Requirements. https://library.wmo.int/index.php?lvl=notice_display&id=22135

Guanter, L., Irakulis-Loitxate, I., Gorroño, J., Sánchez-García, E., Cusworth, D. H., Varon, D. J., ... & Colombo, R. (2021). Mapping methane point emissions with the PRISMA spaceborne imaging spectrometer. Remote Sensing of Environment, 265, 112671.

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 [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

Kangro, K., Pall, A. M., Laugaste, R., Piirsoo, K., Maileht, K., Rahn, I. A., & Alikas, K. (2024). Two decades of cyanobacterial bloom dynamics in a shallow eutrophic lake: remote sensing methods in combination with light microscopy. Hydrobiologia, 1-18.

Li, X., Peng, S., Xi, Y., Woolway, R. I., & Liu, G. (2022). Earlier ice loss accelerates lake warming in the Northern Hemisphere. Nature communications, 13(1), 1-9.

Linsbauer, A. et al., 2016: Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya–Karakoram region. Annals of Glaciology, 57(71), 119–130, doi:10.3189/2016aog71a627.

MacCallum, S. N., & Merchant, C. J. (2012). Surface water temperature observations of large lakes by optimal estimation. Canadian Journal of Remote Sensing, 38(1), 25–45. https://doi.org/10.5589/m12-010

Magnin, F., W. Haeberli, A. Linsbauer, P. Deline, and L. Ravanel, 2020: Estimating glacier-bed overdeepenings as possible sites of future lakes in the deglaciating Mont Blanc massif (Western European Alps). Geomorphology, 350, 106913, doi:10.1016/j.geomorph.2019.106913.

Maxant, J., Braun, R., Caspard, M., & Clandillon, S. (2022). ExtractEO, a Pipeline for Disaster Extent Mapping in the Context of Emergency Management. Remote Sensing, 14(20), 5253.

Pickens, A. H., Hansen, M. C., Stehman, S. V., Tyukavina, A., Potapov, P., Zalles, V., & Higgins, J. (2022). Global seasonal dynamics of inland open water and ice. Remote Sensing of Environment, 272, 112963.

Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C., & Wang, W. (2002). An improved in situ and satellite SST analysis for climate. Journal of climate, 15(13), 1609-1625.

Tang, F., Chen, P., An, Z., Xiong, M., Chen, H., & Qiu, L. (2023). A Dual-Threshold Algorithm for Ice-Covered Lake Water Level Retrieval Using Sentinel-3 SAR Altimetry Waveforms. Sensors, 23(24), 9724.

Tigli, M., Bak, M. P., Janse, J. H., Strokal, M., & Janssen, A. B. (2025). The future of algal blooms in lakes globally is in our hands. *Water Research*, *268*, 122533.

Tom, M., Wu, T., Baltsavias, E., & Schindler, K. (2022). Recent ice trends in Swiss mountain lakes: 20-year analysis of MODIS imagery. PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science, 90(4), 413-431.

Tong, J.， Gao, Y.， Zhan, P.， Song, C. (2024). Advances in lake ice monitoring methods based on remote sensing technology. National Remote Sensing Bulletin, 28（3)541-557 (DOI：10.11834/jrs.20232447) (in Chinese).

Walter, K. M., Engram, M., Duguay, C. R., Jeffries, M. O., & Chapin III, F. S. (2008). The Potential Use of Synthetic Aperture Radar for Estimating Methane Ebullition From Arctic Lakes. JAWRA Journal of the American Water Resources Association, 44(2), 305-315.

Wang, X., Shi, K., Zhang, Y., Qin, B., Zhang, Y., Wang, W., ... & Jeppesen, E. (2023). Climate change drives rapid warming and increasing heatwaves of lakes. Science bulletin, 68(14), 1574-1584.

Woolway, R. I., & Maberly, S. C. (2020). Climate velocity in inland standing waters. Nature Climate Change, 10(12), 1124-1129.

Zeng, C., & Binding, C. E. (2021). Consistent multi-mission measures of inland water algal bloom spatial extent using MERIS, MODIS and OLCI. Remote Sensing, 13(17), 3349.

Zhao, D., Huang, J., Li, Z., Yu, G., & Shen, H. (2024). Dynamic monitoring and analysis of chlorophyll-a concentrations in global lakes using Sentinel-2 images in Google Earth Engine. Science of The Total Environment, 912, 169152

Zhao, N., Fan, Z., & Zhao, M. (2021). A new approach for estimating dissolved oxygen based on a high-accuracy surface modeling method. Sensors, 21(12), 3954.