Consortium Members

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List of Contents

1. Executive summary

This document summarises the user requirements for the Lakes Essential Climate Variable (ECV) collected within the framework of the European Space Agency Climate Change Initiative (http://cci.esa.int/lakes, Lakes_cci).

It synthesises the information obtained through a review of existing reference documents and scientific literature, and collected from meetings of the Climate Modelling User group (CMUG, including related documents), Climate Research Group (CRG) and the wider lake research community, the latter via two surveys. An overview of requirements from Lakes_cci user workshop (22-24 October 2019, Toulouse) is also presented along with a summary of requirements for each thematic variable as reported by the teams involved in CDR generation.

This document has been updated with respect to the first version (URD v1) based on the interaction between Lakes_cci and the climate community, in particular the CMUG as well as on the results gathered form the second survey.

The main outcomes for updating the user requirement issues concerned an identified need for gapless data (for climate modelling), to resolve inconsistencies for some products, to highlight interest in new thematic variables (CDOM, extinction coefficient), to include more lakes and to find ways to reduce the processing and observational expertise needed to exploit the data successfully.

It is noted that this deliverable is issued before Climate Research Data Package v2.0 was published so that the collected requirements may not be representative of the broader community of users that we expect to reach with v2.0. With a major uptake in use of Lakes_cci data we expect increased exploitation of the dataset which would likely raise further usage requirements.

2. Overview

This is an update to the first version of the User Requirements Document for the ESA Climate Change Initiative on the Lakes Essential Climate Variable (ECV). The user requirements describe what is required by users of climate data records (CDRs) of variables describing the state of lakes that are relevant to climate applications.

The European Space Agency (ESA) Climate Change Initiative (CCI) project aims to provide a comprehensive and timely response to the challenging requirements set by the Global Climate Observing System (GCOS) and the Committee on Earth Observation Satellites (CEOS) for highly stable, long-term, satellite-based products for climate research (ESA Climate Change Initiative). As part of the CCI project, Lakes_cci is included in the CCI second phase, and this document provides the second last issue of the user requirements document for this ECV.

Lakes are of significant interest for the scientific and environmental communities. Different disciplines, such as hydrology, limnology, climatology, biogeochemistry and geodesy, are interested in the millions of lakes (from small ponds to inland seas) from local to global scale. Remote sensing can be an opportunity to extend and complement measurements for different scales of spatial-temporal analysis. In such a framework the Lakes_cci project is developing products for the following five variables:

- Lake Water Level (LWL): fundamental for analysing the balance between water inputs and water loss
- Lake Water Extent (LWE): expansion in glacial regions and dryness in temperate zones
- Lake Surface Water temperature (LSWT): this variable is correlated with regional air temperatures
- Lake Ice Cover (LIC): analyse delay in the timing of freeze up in autumn and advance of break-up in spring
- Lake Water Leaving Reflectance (LWLR): this variable is essential to evaluate the water surface characteristics (e.g. phytoplankton concentration and composition).

This document provides an update that now includes Lake Ice Thickness (LIT), one of the thematic variables of the Lake ECV identified in GCOS (2016) but not covered in the baseline, which has been added recently as an R&D option of Lakes_cci.

In this context, Lakes_cci represents a unique framework to provide data to the diverse communities of lake scientists, whose engagement is also relevant for an overall assessment of the utility of the Lakes_cci products. To this aim, the project reviews the relevant requirements in this User Requirements Document (URD).

Previous initiatives based on space observations, such as the NERC GloboLakes project (www.globolakes.ac.uk), have gathered user requirements for applications of satellite data for their target parameters (LWLR and LSWT in the case of GloboLakes), while the Lakes_cci must assess user requirements across all the parameters of the Lakes ECV as defined by GCOS.

Several sources of requirements are reviewed in this URD. Requirements will be more comprehensively addressed in future issues of the URD as the project accumulates more inputs. The present sources are:

1. Global Climate Observing System
2. World Climate Research Programme
3. World Meteorological Programme
4. Meetings of lake-relevant communities attended by team members
5. CCI Climate Modellers' User Group (CMUG)

6. An online survey of users
7. Experience of team members as data users for their own applications

The structure of the document is as follows. Requirements from existing reference documents are reviewed in section 3; this section also focusses on the interaction between Lakes_cci and CMUG. Requirements obtained by interacting with user communities are reviewed in section 4 which illustrates the results obtained from two surveys, the first circulated during the initial phase of the project, the second prepared for this document. Section 4 also provides an overview of requirements from scientific literature, from CRG and from the Lakes_cci user workshop (22-24 October 2019, Toulouse). Requirements evident within the Lakes_cci project finally follow in section 5. In section 6 we synthesise the statement of requirements for each ECV Lakes sub-variable by reporting the diverse sources they were derived from.

3. Requirements from existing reference documents

This chapter reports the requirements from existing reference documents. Sections address the international context (GCOS, WMO and WCRP), and requirements from the CCI Climate Modelling Group.

3.1. Requirements from international reference documents

3.1.1. Requirements from Global Climate Observing System (GCOS)

The Global Climate Observing System (GCOS) defined the Essential Climate Variables (ECVs) required for long-term observation of the atmosphere, the continental surface and sub-surface, and the ocean. GCOS is a joint programme of the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), the United Nations Environment Programme (UNEP), and the International Science Council (ISC). The World Meteorological Organization (WMO) is the specialized agency of the United Nations for weather, water and climate. WMO supports numerous programmes, which cover all aspects of climate research, observations, assessment, modelling and services. The Global climate monitoring supports and serves the programmes of WMO and its Member States. WMO programmes provide information for the mitigation and adaptation to the Earth climate change. Requirements from WMO are subsumed here within the statements of GCOS.

GCOS has identified the *data essential for climate analysis, prediction and change detection,* and stated requirements for the Climate Data Records (CDRs) that quantify the different ECVs.

To ensure that CDRs are sufficiently homogeneous, stable and accurate for climate purposes, they should fulfil two types of requirement as defined by GCOS:

(a) Generic requirements that are applicable to all ECVs, which are contained in the GCOS Climate Monitoring Principles (GCMP);

(b) ECV-product specific requirements.

The GCOS climate monitoring principles are listed as Table 1.

Table 1. Global Climate Observing System climate monitoring principles (Revised Reporting Guidelines as agreed by the UNFCCC, Bali, Dec 2007, decision 11/CP.13; data source: GCOS 200)

Effective monitoring systems for climate should adhere to the following principles:
(a) The impact of new systems or changes to existing systems should be assessed prior to implementation;
(b) A suitable period of overlap for new and old observing systems is required;
(c) The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (i.e. metadata) should be documented and treated with the same care as the data themselves;
(d) The quality and homogeneity of data should be regularly assessed as a part of routine operations;
(e) Consideration of the needs for environmental and climate-monitoring products and assessments, such as Intergovernmental Panel on Climate Change assessments, should be integrated into national, regional and global observing priorities;
(f) Operation of historically-uninterrupted stations and observing systems should be maintained;
(g) High priority for additional observations should be focused on data-poor regions, poorly-observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution;
(h) Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators and instrument engineers at the outset of system design and implementation;
(i) The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted;
(j) Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.
Furthermore, operators of satellite systems for monitoring climate need to:
(a) Take steps to make radiance calibration, calibration-monitoring and satellite-to-satellite cross-calibration of the full operational constellation a part of the operational satellite system;
(b) Take steps to sample the Earth system in such a way that climate-relevant (diurnal, seasonal, and long-term interannual) changes can be resolved.
Thus satellite systems for climate monitoring should adhere to the following specific principles:
(a) Constant sampling within the diurnal cycle (minimizing the effects of orbital decay and orbit drift) should be maintained;
(b) A suitable period of overlap for new and old satellite systems should be ensured for a period adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time-series observations;
(c) Continuity of satellite measurements (i.e. elimination of gaps in the long-term record) through appropriate launch and orbital strategies should be ensured;
(d) Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be ensured;
(e) On-board calibration adequate for climate system observations should be ensured and associated instrument characteristics monitored;
(f) Operational production of priority climate products should be sustained and peer-reviewed new products should be introduced as appropriate;
(g) Data systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained;
(h) Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when these exist on decommissioned satellites;
(i) Complementary in situ baseline observations for satellite measurements should be maintained through appropriate activities and cooperation;
(j) Random errors and time-dependent biases in satellite observations and derived products should be identified.

GCOS has defined the thematic variables or parameters of the Lakes ECV and made ECV-specific requirements summarised in Table 2. The "Lakes ECV" comprises 6 variables, requiring observational methods and systems that are independent to a significant degree.

Table 2. GCOS target requirements for Lakes ECV products (GCOS-200)

Product	Lake Water Level	Lake Extent (or Lake Area)	Lake Surface Water Temperature	Lake Ice Thickness (LIT) Lake Ice Cover (LIC)	Lake Water Leaving Reflectance (or Lake Colour)
Required measurement uncertainty	3 cm for large lakes 10 cm for the reminder	10% (relative) 5% (for 70 largest lakes)	1°K	LIT: 1-2 cm LIC: 10%	30%
Stability	1 cm/decade	5% /decade	0.1°K per decade	LIT: N/A LIC: 1% /decade	1% /decade
Spatial resolution	100 m	20 m	300 m	LIT: 100 m LIC: 300 m	300 m
Temporal resolution	daily ground-based or satellite observations	daily changes	weekly observations	LIT: monthly LIC: daily observations	weekly observations

The numerical value of the required measurement uncertainty (first record in Table 2) is defined by GCOS as the target uncertainty with a coverage factor of 2. This means that in order to obtain the required standard uncertainty of the named quantity (the usual presentation), this value should be divided by 2.

As with any such distillation, Table 2 cannot be considered definitive for all potential users. We therefore treat this list of requirements as a starting point for the Lakes_cci project, while a refined list will be provided based on experts and users consultation within the Lakes_cci ([TR-40]; "TR" refers to a numbered technical requirement of the Lakes_cci project).

Lakes are part of the hydrological component of the Terrestrial Climate Observing System (TCOS). GCOS (2016) detailed significant improvements in the observation of terrestrial ECVs, mainly due to satellite observations. However, some gaps and areas for improvement has been identified, both in GCOS (2016) and GCOS (2010). Of particular interest for the Lakes ECV component are:

(a) Improving the reporting and dissemination of hydrological data. Many observational data on hydrological ECVs, such as those for rivers, lakes and groundwater, are not internationally available. Under WMO Resolutions 25, 40 and 60, such data should be freely exchanged for climate uses.

(b) Global, satellite-based products need to be produced in continuous operations for many ECVs. (Note that the GCOS requirements in Table 2 do not capture requirements for data latency.)

(c) Terrestrial satellite and ground-based observations are important for many purposes, including sustainable management of natural resources and biodiversity; improving the coordination of terrestrial observations will thus enhance the efficiency and coverage of observations. WMO provides some coordination for the hydrosphere and cryosphere, while coordination across the terrestrial domain and between ECVs is still lacking.

The GCOS (2016) identified a number of actions to improve the monitoring of ECVs and to set research tasks needed to underpin future improvements, which are listed in Table 3 only for Lakes ECV. Finally, Table 4 provides actions that aim at improving the observation of Lakes ECV.

Table 3. Summary of Lakes ECV actions

Continue existing observations	*Action T9 - Submit historical and current monthly lake-level data* Action: Continue submitting to HYDROLARE (International Data Centre on Hydrology of Lakes and Reservoirs) historical and current monthly lake-level data for Global Terrestrial Network – Lakes (GTN-L) lakes and other lakes, as well as weekly/monthly water-temperature and ice-thickness data for GTN-L Benefit: Maintain data record Who: National Hydrological Services through WMO CHy and other institutions and agencies providing and holding data
Improve existing networks	*Action T8 - Lakes and reservoirs: compare satellite and in situ observations* Action: Assess accuracy of satellite water-level measurements by a comparative analysis of in situ and satellite observations for selected lakes and reservoirs. Benefit: Improved accuracy Who: Legos/CNES, HYDROLARE *Action T10 - Establish sustained production and improvement for the Lake ECV products* Action: Establish satellite-based ECV data records for Lake-surface water temperature, Lake ice coverage and Lake water-leaving reflectance (Lake colour);Implement and sustain routine production of these new satellite based products; Sustain efforts on improving algorithms, processing chains and uncertainty assessments for the new ECV products, including systematic in situ data sharing and collection in support of ECV validation; Develop additional products derived from Lake water-leaving reflectance for turbidity, chlorophyll and coloured dissolved organic matter. Benefit: Add additional Lake ECV products for extended data records; provide a more comprehensive assessment of climate variability and change in lake systems Who: Space agencies and CEOS, Copernicus Global Land Service, GloboLakes and ESA CCI
Improve data stewardship	*Action T7 - Exchange of hydrological data* Action: In line with WMO Resolutions 25 (Cg-XIII) and 40 (Cg-XII), improve the exchange hydrological data and delivery to data centres of all networks encompassed by Global Terrestrial Network – Hydrology (GTN-H), in particular the GCOS baseline networks, and facilitate the development of integrated hydrological products to demonstrate the value of these coordinated and sustained global hydrological networks. Benefit: Improved reporting filling large geographic gaps in datasets Who: GTN-H partners in cooperation with WMO and GCOS

Table 4. Issues identified for Lakes within hydrological observations

ECV	Significant findings in the GCOS 2015 Status Report
Lakes	More WMO Members need to transmit i*n situ* hydrological data to HYDROLARE. Satellite-based altimetry observations need to be continuously updated. The accuracy of satellite-based water-level observations requires further improvement. In situ validation of satellite-based water-level observations is of critical importance.

With respect to GCOS, the CCI projects were informed by CMUG (See section 3.2) about a review phase to be updated by 2022 to redefine the GCOS ECV thresholds (minimum requirements), breakthroughs and goals. The Lakes_cci consortium have taken the opportunity to provide feedback on some of the thematic variables (e.g. LSWT, LWLR, LIC).

3.1.2. Requirements from World Climate Research Programme (WCRP)

The World Climate Research Programme (WCRP) plays a prominent role in supporting and promoting internationally coordinated climate science with global and regional impacts. In the regional context ("Regional Climate"), the focus of WCRP remains on enhancing the scientific basis to understand regional climate and its changes; identifying, quantifying and delivering high quality, reliable and accessible regional climate information, the needs for which are identified by regional stakeholders. In particular, it is active in Polar, Monsoon and Tropical regions. The scope of WCRP activities does not include climate services, but includes providing science-based, reliable and locally relevant information on which climate services and impact assessments can be built. Addressing this objective, WCRP thrives to bridge the identified gaps between data producers and data users, and between research science and operational services.

One the four WCRP core projects is the Global Energy and Water Exchanges (GEWEX). The GEWEX has the mission to observe, understand and model the hydrological cycle and energy fluxes in the Earth's atmosphere and at the surface, within the perspective to predict changes in the world's climate.

GEWEX imperatives are described in GEWEX (2012). A key question identified is to distinguish natural variability, climate-change forced variability and land-use related variability. This leads to a statement of requirement relevant to the lake ECV: it is required to have

- a compendium of trends in key land surface variables for which there is a sufficient observational basis to identify long-term (multiple decades to century) trends … [to include] lake freeze-up and thaw dates ... [with] consistency of spatial resolution with that of coupled models

3.2. Requirements from Climate Modelling User Group

Within the CCI programme, the Climate Modelling User Group (CMUG) interacts with the climate research group of each project, including Lakes_cci. In particular, CMUG brings a climate system perspective to the CCI programme and provides a dedicated forum through which the Earth Observation and climate modelling communities can work closely together.

Cooperation between the project and CMUG will centre on the Climate Science Working Group (CSWG), coordinated by CMUG and with participation of the CRG from each ECV project as noted in the SoW.

The roles of CMUG include identifying water bodies and indicating the requirements in terms of data availability and uncertainty. CMUG will review product performance by applying CDRs to model validation and assimilation and will help improving the requirements for each ECV and their derived components, in order to demonstrate the value and limitations of the products within the modelling community.

3.2.1. Interactions with CMUG

The interaction of Lakes_cci with CMUG was achieved in two ways; a first method is based on attending CMUG and CSWG meetings, a second method on analysing the relevant documents delivered by CMUG.

In particular, two CMUG integration meetings were attended in person, while the latest two CSWG meetings organised in 2021 were attended remotely; the following sections describe salient outcomes from all four meetings.

3.2.1.1. CMUG Integration meetings

First meeting, Exeter, UK, October 2018

The first interaction with CMUG within the Lakes_cci project occurred at the CMUG colocation (Met Office, Exeter, UK, October 2018). There, we had the opportunity to present an overview of the project and interact with CMUG as well as with the other CCI ECVs. The meeting was attended by one Science Lead, by the members of CRG from each of the nine new ECV projects, and by researchers from many of the existing CCI ECV projects.

To foster the interaction between ECV projects and CMUG, the meeting was organized based on specific aims such as:

- look at the plans of the new ECVs projects with regard to the needs of the Climate Research Community, CMUG and GCOS requirements;
- let CMUG show their plans to the CCI ECV projects to discuss links and potential synergies;
- let the ECV teams and CMUG explain how their work might be carried on under the integrated perspective required for consistency between ECVs;
- discuss how to deal with uncertainties in products (how to capture and report them to product users);
- let CMUG and the existing ECV teams demonstrate 'best practices' to the new ECV teams.

The first interaction helped us to define the following requirements from CMUG:

- Uncertainty: the same language should be used to describe uncertainties across all ECVs. The recommendations from Merchant et al. (2017) were adopted as guidelines for consistency across all ECVs.
- Consistency:
  - the land-water mask should be consistent for all CCI CDRs and should be traceable to the one provided by the Land Cover CCI. This does not imply that all thematic variables within Lakes_cci must provide data for the same set of pixels within a defined lake area, as additional masking is required for most variables. However, the definition of the observed lake area must be consistently based on LandCover_cci.
  - a matrix (Figure 1) of CDRs needing cross-ECV consistency was compiled based on the opinion of the CMUG. Green boxes indicate that the projects named on the top row depend on the project named in the vertical left column.

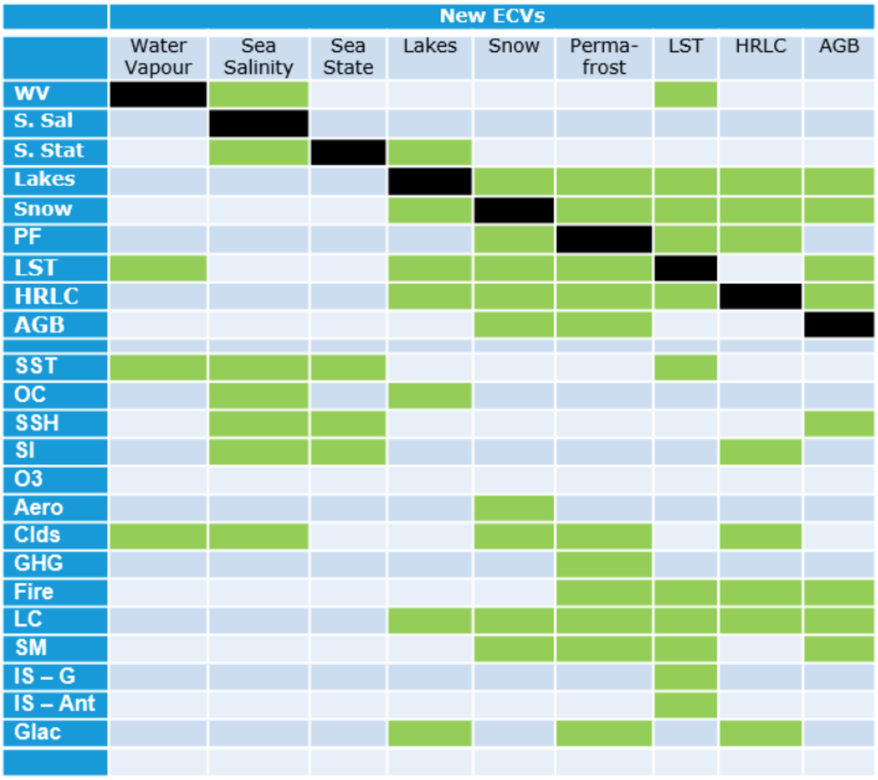


Figure 1. Dependencies between the new CCI ECV projects and all the CCI ECV projects

- CMUG and ECVs interaction:
  - During the last CMUG meeting (Exeter, October 2018), UK Met office expressed the interest in evaluating lakes effects on local temperature, involving two ECVs (Lakes and LST), inside the activities of CMUG WP3.7. This latter is included in the Task 3, which aims at assessing the consistency and quality of CCI products across ECVs.
  - During the CSWG meeting of CMUG organized remotely on 29 May 2019, the need to circulate the agenda of CCI quarterly report meetings was expressed so that CMUG can attend in case of interest. This coordination might be adopted by Lakes_cci to easily get and update the requirement of CMUG activities, and in particular the one related to WP5.

Second CMUG Integration meeting, Barcelona on 6-7 November 2021

The CMUG integration meeting was held in Barcelona on 6-7 November 2021 with about 80 participants. A plenary session was followed by a poster session and by two parallel sessions titled Science Leads and CSWG, respectively.

During the Plenary session a presentation was given on “GCOS ECV, background, plans and developments”. GCOS focuses on observations, data transmission, data management, with 54 physical or biological ECVs divided into atmosphere, land and ocean compartments. Three expert panels are engaged in the ECVs review, based on the Earth cycles (energy, carbon and water) as already assigned in the previous meeting in March 2019. In perspective, new studies are in place for air/sea energy fluxes, coastal-land-ocean-water fluxes, and extreme events. One of the following steps will be the review of the list of ECV product requirements (G10). The GCOS review is ongoing and is to be updated by 2022 to define thresholds (minimum requirements), breakthroughs and goals for ECVs requirements. As the review is public, the consortium has taken such opportunity to provide feedback on some thematic variables (e.g. LSWT, LIC).

Then, a presentation was given on “CMUG results to date”. The document D1.1 reports the CMUG user requirements: i) spatial resolution < 10 km or higher; ii) temporal resolution, daily or higher; iii) similar temporal/spatial resolutions among different ECVs; iv) the tools for exploring the data are sufficient; v) GCOS requirements reflect their data needs.

During this meeting it was notified that Lakes ECV (one of the new CCI ECV) does not comply with quality, uncertainty, maturity and GCOS requirements yet.

Then the presentation of the “D1.2_Foresight” report followed. D1.2 aims at assessing the requirements for EO developments in support of the climate modelling and information community, and informing the new 2022 ESA Climate programme proposal via a broad community consultation. The main outcomes were i) the definition of climate information services requiring EO, for example “Monitoring natural resources”, which needs data on water resources and quality, land cover; ii) the identification of EO activities and gap analysis necessary to improve the EO products assimilation and reanalysis, as well as their use for defining and modelling climate variability and change.

The link between Lakes_cci and CMUG inside the activities of CMUG WP3.7 was confirmed (as part of Task 3, “assessing the consistency and quality of CCI products across ECVs”) on key questions, such as “What effect does lake temperature (or other parameters) have on surrounding LST?”. In addition, within WP3.7, a Regional Climate Model (RCM) is to be run over Europe.

The last contribution to the Plenary session regarded the new WCRP (World Climate Research Programme) strategy for the period 2019-2028. The strategic plan has four objectives: i) emphasis on climate dynamics and reservoirs and flows; ii) improve prediction capabilities with a better use of existing observations; iii) long term climate change and simulation capabilities; iv) interactions with social systems and public engagement. Some limits were reported on the current research effort and capabilities of CMUG to exploit the CCI ECVs. In particular, the presence of different tools and different formats (e.g., ESA CCI, ESFG, C3S), as well as the use of different interfaces among the same/similar community, is confusing and causes a loss of resources.

The Poster session on CCI ECVs included results for all 23 CCI ECV projects plus the x-cutting projects, data projects and Climate from Space app. Lakes_cci project presented a contribution titled “Delivering the Lake Essential Climate Variable: An update from ESA CCI Lakes” to present the main objectives, the CRG activities and the Users requirements, together with the timing on the availability of the first version of the dataset.

During a Science Leads parallel session a discussion was held on the gap analysis report. One of the main questions that arose was “how to join activities between ECVs”. A couple of examples on some cross ECV containing gaps were reported. Each science leader was asked to point out what was missing in their own competence area. In the next phase ESA will look deeper into cross ECV, and for these cases it was suggested to share common case-studies. In addition, the need of a more efficient structure arose, for creating a common shared document to report what has been already in place. Modelling was really a key at the beginning of CCI, but there is currently the need to be more focused on what is being produced to forecast the future. The availability of multi-sensors and satellite products within CCI is a key element, but data harmonization is crucial as well. In addition, CCI dataset has to be connected to Copernicus C3S. it was stressed that a mapping between C3S and CCI ECV datasets is crucial to avoid confusion to users.

During the CSWG parallel session, people involved in the different ECVs worked in groups to answer to some questions:

i) how does your ECV contribute to a fundamental understanding of the climate system (Carbon cycle, Water cycle, Land-atmosphere-ocean interactions, Radiation budget, Ice sheets and permafrost)? The **ECV Lakes is involved with different importance in all systems**.

ii) what research questions could be answered by working with other ECVs? The need to use ECVs together to improve parameterizations and uncertainty modelling was assessed. ECVs could constrain one another during their retrieval (*e.g.*, SST could constrain water vapour). A rather impressive fleet of satellites is available to tackle cycles/fluxes/processes for ECVs. In this regard, improving data assimilation could help learning how well the processes are represented.

iii) When bringing together multiple datasets, what challenges do you face and how would you overcome them? The answer dealt with issues related to temporal and spatial and technical consistency; data policy; mismatch between models and observations (parameters/resolution/timespan/uncertainty/data format are not the same); simulators present for some ECVs but not for others; mapping modelled/observed ECVs (OBS4MIPS): Observation operators, CDF-matching, and more communication between ECVs.

The need for more discussion and efficient interaction between CMUG and CCI+ activities was highlighted.

3.2.1.2. CSWG meetings

CSWG - focus on Fire, LC, HRLC and Biomass

The CSWG on Fire, Land Cover, High Resolution Land Cover, and Biomass ECVs was held online on 18th January 2021. Fire_cci presentation informed that new product reporting burnt areas was released a few weeks earlier “FireCCI51 is available for years 2001 to 2019”. They found that 90% of the small fires were being missed in coarser resolution products. In addition, high resolution land cover presentation, including input from CRG, identified those areas (Amazon, Africa, Siberia) where it is aimed to provide high resolution land cover products (i.e. 10m for 2019and 30m every 5 years).

CSWG - Focus on Lakes, Snow and Permafrost ECVs

There are a variety of ways in which CMUG formally provides feedback to the CCI projects. These include presentations at CSWG meetings, written reports, and documents such as the User Requirements document, through which feedback are shared across all of CCI programme. In such a framework, the CSWG on Lakes, Snow and Permafrost ECVs was held on-line on 7th May 2021.

A first presentation was titled “**CMUG work on Lakes**”. From this first the issue of **data gaps** within the Lakes_cci LSWT dataset emerged. As a consequence, this product is not being used in favor of the ARC3 data. A discussion was held on who should fill in the data gaps. Is it the CCI project team, after making some assumptions, or is it the user who will create their own dataset consistently with its own scope? Dr. Erasmo Buonomo believes that this should always be done by experts and that the CCI project would seem to be the best place for such an activity. The reconstruction carried out for the ARC3 data was complex since the optimal strategy for gap filling can vary between lakes and it is necessary to understand the error characteristics and data correlations so that the work is data driven. This issue also concerns all other ECV projects. It is worth considering how this responsibility may vary across the different cases, ECV projects, different models etc. There was some discussion about the possibility of using data assimilation for reconstruction. No European meteorological service currently assimilates LSWT, although the OSTIA SST analysis system includes very large lakes using operational SST data flows (that sometimes also address very large lakes) and the ARC3 climatology as background. **FLake was also mentioned as a system used in NWP** at the Met Office and SMHI, providing the linkage with the Lakes_cci user workshop. The possibility of using climatology to replace the need for gap filling was raised.

The CCI projects on Snow and Permafrost were then presented. In breakout groups a concern on the potential use of Lakes_cci LSWT data was raised, as such data seem too coarse for very small, scattered water bodies common across high latitude landscapes. An interest in using **Landsat thermal data** emerged because of higher resolution, although observation frequency and accuracy are limited.

Finally, the Lakes_cci project was presented by Dr. JF Crétaux to outline how the Lakes_cci might work in synergy with Snow and Permafrost CCIs. It was discussed how Lakes_cci provides some information regarding the stability of **LWE** and how some lakes greatly vary in their extent. Based on recent findings from Dr. JF Crétaux on drivers of variability of Tibetan Plateau lakes, two main reasons for LWE variability are typically addressed by researchers: one is glacier and permafrost melting, and the other is precipitation variability. From a literature review, Lakes_cci verified that most studies attribute the majority of **LWE** (70%) to **rainfall changes**, reinforcing the need of having a new CCI on **precipitation**.

Three more presentations regarded the "Use of Snow and Permafrost ECVs", the "CCI Snow" and the "CCI Permafrost", both including inputs from CRG. CMUG reported that the SWE (snow water equivalent) product was used together with the permafrost mean ground temperature. At the time the experiments were carried out, the Snow Cover Fraction product from snow_cci was not available and the IMS product was used instead. Snow_cci team was working towards Version 2 for the CDRs expected to be released by October 2021.Permafrost_cci was working at the Version 3 of the products.

In the last part of the meeting, feedback for CMUG were collected. It was suggested to design the CMUG experiments in coincidence with the time availability of the CCI products. A positive feedback was given to the platform for the CSWG meeting, which allowed to have the ECVs grouped together. **Finally, it was suggested to invite a a CMUG representative to the next CRG meetings**.

3.2.1.3. Review of CMUG related documents

During its activity the CMUG produced two deliverables that gave important feedback to all CCI ECV projects. In particular, the D1.1 (v2.2) titled "Meeting the needs of the Climate Community – Requirements" and the D2.3 (v1.3) on the "Suitability of CCI ECVs for Climate Science and Services" were considered relevant for our project and hence reviewed in this section.

D1.1 "Meeting the needs of the Climate Community – Requirements"

The purpose of the D1.1 was to assist the CCI ECV projects and cross-ECV demonstration projects in focusing on the needs of the Climate Modelling Community (CMC), Climate Research Community (CRC) and other expert users of climate data.

Generic requirements on the use of CCI ECVs for climate applications were gained from the CMUG user surveys and expert interviews. A synthesis is reported in Table 5.

Table 5 Use of CCI ECVs for different climate applications (from D1.1). Yellow boxes and stars highlight applications related to Lakes.

CCI ECV	Model Initial-isation	Prescribe Boundary Conditions	Re-analyses	Data Assimilation	Model Development and Validation	Climate Monitoring/ Attribution	Q/C in situ data	Climate process study	Other, inc. Climate Services
Atmospheric									
Water Vapour	X	X	X		X	X		X	X
Clouds	X	X				X	X	X	X
Ozone	X	X	X	X	X	X	X		X
Greenhouse Gases	X	X	X	X	X	X	X		X
Aerosols	X	X	X	X	X	X		X	X
Oceanic									
Sea State	X	X	X	X				X	X
Sea Surface Salinity	X	X						X	X
SST	X	X	X		X	X			X
Sea Level	X	X	X	X	X	X			X
Sea-ice	X	X	X		X	X		X	X
Ocean Colour				X	X	X		X	X
Terrestrial									
Above Ground Biomass	X	X		X	X	X	X	X	X
Land Surface Temperature	X	X	X	X	X	X	X	X	X
Permafrost	X	X	X		X	X		X	X
Lakes	★	★			★		★	★	★

Most of the 23 CCI ECVs have potential for model initialisation through improving the representation of the surface fields. The stability and accuracy requirements for initialisation are more relaxed than for climate monitoring as the initial uncertainties in the model fields without the observations are often far greater than the measurement uncertainty.

Satellite observations are a key part of the development and evaluation of climate models, and in **climate research** the coupling of various components in modelling is a priority. Terrestrial ECVs contribute to model development and evaluation, for example the observed changes in AGB, LST, Land Cover, **Lakes**, Permafrost, Snow, Fire and SM contribute to a process-level understanding. For the satellite observations to be used in model evaluation, the ECV accuracy must be compared to the magnitude of the model error, in fact the dataset is useful as long as the accuracy is better than the model error.

In the recent years, the need for a better initialisation of seasonal and decadal hindcast or forecast models has become clear for operational forecasting centers. To be assimilated within the models, an ECV must be represented as a prognostic variable. **Lakes_cci variables data assimilation is currently** feasible as reported in Table 5.

There are other research areas that use, or have the potential to use, CCI data: LST, **Lakes**, and AGB can **be potentially used by the Copernicus Global Land Monitoring Service** to support the provision of products for e.g. agriculture, forest, hydrology, to users.

In addition to the CDR quality requirements, there is a generic set of principles for ECV data quality. **Traceability from satellite measurements** through bias correction to ECV data is essential for the integrity of any Climate Data Record. The GSICS initiative is important to improve the quality of the global satellite datasets. The FIDUCEO project developed methods and tools (Mittaz et al., 2019) for guaranteeing consistency among in satellite derived CDRs. These methods can be used by the CCI ECVs in order to produce climate quality data.

Then, a chapter was dedicated on **specific requirements for each CCI ECVs**. The main points regarding Lakes are the following.

Reanalysis of lake parameters is useful in the context of regional climate modeling (Giorgi and Gutowski, 2016). The inclusion of lake variables would work as an **observational constraint**, either for Regional Climate Models (RCMs) relying on their land surface schemes and having basic description of lakes, or for those RCMs having more refined lake components. To this aim, lake reanalysis should be available on sufficiently long periods to allow climatological analysis, with a good overlap with existing reanalyses, and consistent with them in terms of resolution and accuracy, including the accurate representation of existing trends on lake temperature and ice fraction.

The main parameters required for shorter timescale **NWP modelling** (seasonal/decadal) are **LWE** and **depth** as ancillary inputs. In future, depth and LWE changes may also be required, although currently available models (e.g. Met-UM) can't handle them at present. A Global Lakes Data Base (GLDB) has been set up for NWP applications containing information about lake location (latitude, longitude), water surface area, and lake mean and max depths. This is the sort of information which is most useful on NWP scales.

LSWT is the main output of the **FLake** module used in the Met-UM, so **LSWT observations** would be useful along with **LIC** and **LIT** both as an **input and for model validation**. In the future it will also be relevant to provide the **extinction coefficient**, and to distinguish between lakes which are **freshwater** and those which are **salt water**.

Lake colour (**hence LWLR**) will be useful when carbon budget modelling starts to take into account the role of lakes.

In Table 6 the detailed requirements for the Lake_cci parameters are listed. For each requirement, the source is also indicated.

Table 6. Requirements for satellite derived Lake observations (LWL, LWE, LSWT, LIT, LIC, Lake Colour).

Parameter	Application	Horizontal Resolution	Observing Cycle	Precision	Accuracy	Stability	Error Type (see table 3)	Source
Lake water level	GCOS 2016	100 m	Daily	3cm for large lakes; 10cm for the remainder	3cm for large lakes; 10cm for the remainder	1cm / decade		WMO
	Trend monitoring	1km / 100m	Daily	3cm for large lakes; 10cm for the remainder	3cm for large lakes; 10cm for the remainder	1cm / decade	ERRMERG	MO
	Seasonal / Decadal forecasting	25 km	1 week	3cm for large lakes; 10cm for the remainder	3cm for large lakes; 10cm for the remainder	1cm / decade	SSEOB	MO
	Reanalyses	10 km	12 h	3cm for large lakes; 10cm for the remainder	3cm for large lakes; 10cm for the remainder	1cm / decade	ERRCOV	MO
Water extent	GCOS 2016	20m	Daily	10% (relative); 5% (for 70 largest lakes)	10% (relative); 5% (for 70 largest lakes)	5% / % / decade		WMO
	Trend monitoring	100 m	Daily	10%	10%	5% / decade	ERRMERG	MO
	Seasonal / Decadal forecasting	10 / 25 km	1 week	10%	10%	5% / decade	SSEOB	MO
	Reanalyses	10 / 25 km	Daily	10%	10%	5% / decade	ERRCOV	MO
Lake surface water temperature	GCOS 2016	300m	Weekly	1K	1K	0.1K/decade		WMO
	Trend monitoring	300 m	Daily	0.1K	0.1K	0.01K/ decade	ERRMERG	CMUG survey
	Seasonal / Decadal forecasting	10 / 25 km	1 week	0.1K	0.1K	0.05K/ decade	SSEOB	CMUG survey

	Reanalyses	10 / 25 km	Daily	0.1K	0.1K	0.05K/ decade	ERRCOV	CMUG survey
Lake ice thickness	GCOS 2016	100m	Monthly	1-2cm	1-2cm			WMO
	Trend monitoring	<200 m	Weekly	5cm	5cm		ERRMERG	MO
	Seasonal / Decadal forecasting	10 / 25 km	1 week	10cm	10cm		SSEOB	MO
	Reanalyses	10 / 25 km	Daily	10cm	10cm		ERRCOV	MO
Lake Ice Cover	GCOS 2016	300m	Daily	10%	10%	1%/dec ade		WMO
	Trend monitoring	200 m	Weekly	10%	10%	1%/dec ade	ERRMERG	MO
	Seasonal / Decadal forecasting	10 / 25 km	Daily	10%	10%	1%/dec ade	ERRCOV/SSEO B	MO
	Reanalyses	10 / 25 km	Daily	10%	10%	1%/dec ade	ERRCOV	MO
Lake Colour	GCOS 2016	300m	Weekly	30%	30%	1%/dec ade		WMO
	Trend monitoring	300 m	Weekly	30%	30%	1%/dec ade	ERRMERG	MO
	Seasonal / Decadal forecasting	10 / 25 km	Weekly	30%	30%	1%/dec ade	ERRCOV/SSEO B	MO
	Reanalyses	10 / 25 km	Daily	30%	30%	1%/dec ade	ERRCOV	MO

Another section of D1.1 dealt with the cross-ECV requirements. Some inputs and links between ECVs were reported. The need of a common terminology was identified to enhance communication across the CCI programme.

The ECV projects should all use the same level 1 datasets as input to their level 2 processing. Some ECVs will benefit from the access to other ECV data sets available within the CCI programme to explore synergies and take advantage of opportunities where one ECV's retrieval can benefit from another (Table 7). **Input for Lakes_cc**i can come from **Glaciers, Snow, PF, LST, HRLC** and **AGB**. On the other hand, Lakes can provide input for Ocean colours, Glaciers, Sea state, Snow, LST and HRLC.

The use of **common ancillary fields is important**; for example, **ERA5 should be the preferred source of atmospheric fields**, which would ensure a consistent assumption about the atmospheric state for all ECV datasets. If this is not done, inevitable inconsistencies will be seen in the products which will be only due to different representations of the atmosphere/surface conditions being assumed. In particular, it was suggested **that all ECV projects adopt a common land/sea/lake mask**, **as the one produced by the LC CCI team**. The horizontal grids should be common to level 3 products to ease the comparison and processing of data from different ECV CDRs. Moreover, the definition of atmospheric layering should be common across ECVs (e.g. aerosol and clouds) for level 2 and 3 products.

Finally, the **specification of uncertainty characteristics should be provided in a consistent way and, where appropriate, separated into precision, accuracy and stability**. The errors should also be specified, where possible, for each individual measurement.

Table 7. An analysis of cross linkages between ECVs indicating where links can be made towards consistency. The left-hand column is the project with the identified need (green), the top horizontal row is the provider (yellow).

	SST	Sea level	Clds	Sea ice	OC	Aer'l	GHG	LC	Fire	O3	Glacs +ICs	Ice S.	SM	WV	SS Sal	SSt.	Lake	Snow	PF	LST	HR LC	AGB
SST		X	X	X	X	X								X	X	X				X		
Sea level	X			X				X			X	X	X		X	X						
Clouds	X			X	X	X	X	X	X	X			X	X	X			X	X		X	
Sea ice	X	X	X		X										X	X						
Ocean colour	X		X	X		X									X		X					
Aerosol	X		X	X	X		X	X	X	X			X					X				
GHG		X	X		X	X	X	X	X	X		X							X			
Landcover		X	X			X	X		X	X	X	X	X									
Fire			X			X	X	X		X	X		X									
Ozone	X		X	X		X	X															
Glacrs+ICs		X						X				X	X				X		X		X	
Ice Sheets	X	X			X						X									X		
Soil moisture		X	X				X	X	X		X											
WV	X		X												X					X		
SSS	X	X		X																		
S. State	X	X		X											X		X					
Lake											X							X	X	X	X	X
Snow																	X		X	X	X	X
Permafrost				X														X		X	X	
LST													X	X			X	X	X			X
HRLC								X									X	X	X	X		X
AGB								X	X				X					X	X			

A section of D1.1 was then dedicated to requirements for data formats and data access. The general feedback from the CMUG survey was that the major obstacles in the use of currently available satellite data are the lack of user-friendly information and traceability. This highlights the need for better documentation and uncertainty information as the key flaws in current CCI standards. In details:

- Data formats: the majority of CMUG survey respondents (83%) preferred NetCDF as a file format, in agreement with the CCI Data Standards.
- Data access:
    - 71% of the respondents requested FTP access, 37% requested web access via a browser (http:), 13% through OpenDAP, while some indicated a preference for access through another channel
    - There is a need to be able to subset in time and space the datasets in a convenient way, such as OpenDAP.
    - In addition to access the data from the CCI Open Data Portal, or from the Copernicus CDS, data could be hosted on a node of the Earth System Grid Federation (ESGF) so that users will have the same access interface for European, US and other climate datasets.
- Level of processing: CMUG recommends that ECVs are made available at all possible processing levels (level 1 = geophysical measurements e.g. radiances; level 2 = derived products on original space view; level 3 = daily, monthly means gridded products) and, where possible, both as merged and as single sensor products.
- Geospatial projections: provide simple tools to translate between any projection and a basic lat/lon grid. The CCI datasets should, where possible, share a common projection to facilitate the joint analysis of different datasets from different ECVs. Land/Sea/Lake and Cloud masks are also important for consistency among the ECV projects. Those CCI masks produced in CCI Phases 1 and 2 should be propagated to the new ECV projects in CCI+, otherwise inconsistencies will be seen due to the use of different masks.

D2.3 "Suitability of CCI ECVs for Climate Science and Services"

The purpose of the D2.3 was to review the documentation of ESA CCI+ projects for providing feedback to ESA and the CCI teams.

For Lakes_cci, the User Requirement Document (URD) v1.1 and the Product Specification Document (PSD) v1.2 were reviewed and some feedback on data quality were also supplied.

On the URD v1.1, the comment was that the user requirements are well covered by the document, and that the survey carried out was comprehensive and useful as identified minimum and target standards. One issue was remarked by users on the need of high frequency lake data without gaps, but this criterion was not matched by the preliminary assessment of products currently available. In the GCOS climate monitoring principles, a regular assessment of data quality is also requested. Given the data gaps that currently exist in the product, there is a need for a tool to fill these in a useful way.

On PSD v1.2 a comment regards the need to have variables available on their native grid as well as at the standard 1/120 degree grid.

Data size is a big issue. The total Lake CCI data set is near 2 Tb in size, and it would be much easier to handle if there was an option to download variables individually, by also for specific lakes ore regions across all variables, as well as the full set.

A specific paragraph was dedicated to 'data quality'. The CMUG WP3.7 plans to run a Regional Climate Model (RCM) over Europe. The goal is to feed the RCM with LSWT and Lake Ice products to assess how the use of lake ancillary information impacts the model's ability to reproduce Land Surface Temperature (using the LST ECV observations for comparison). However, post processing and interpolation was needed due to the patchy nature of satellite data, as the RCM relies on coherent spatial data in time and space with no missing points. During some months of the expected simulation time, based on WP3.7 plans over Europe, the computational grid would have had only a few days of non-missing data per month. CMUG are instead considering the use of the ARC3 dataset for an RCM experiment to test the effect of prescribed lake temperature on existing temperature biases over Europe. The ARC3 dataset is based on a physical reconstruction of lake data from satellite observations. Such reconstruction requires specific scientific expertise for its completion, should be addressed in projects aimed at producing data for general use. A successful result of the RCM experiment would support this requirement.

Thus, to the modeling purpose, a reconstruction performed with techniques similar to those applied to the ARC3 lake dataset would make the data much more useful, in particular for Lake Ice and LSWT, which are both required by RCM. In fact, the processing and observational expertise needed to use the Lake CCI datasets is a barrier to their use at the moment for the climate community, and in particular for modellers.

4. Requirements collected by the lake community

4.1. Lakes_cci User Workshop 22-24 October 2019 (Toulouse)

The Lakes_cci User Workshop was organized in combination with the 6th workshop 'Parameterization of Lakes in Numerical Weather Prediction (NWP) and Climate Modelling' (Toulouse, 22-24 October 2019; http://www.meteo.fr/cic/meetings/2019/LAKE2019/). The principal aim of this common workshop was to exchange knowledge on lake remote sensing and on lakes parameterizations in climate models. A total of 32 talks and 51 participants finally registered to the workshop, one of the topics was on Remote sensing applied to lakes in the global climate change scenario. The Lake-cci project was well represented with the participation of 8 people, four talks and two session chairs.

The principal outcomes were:

- **FLake** is a widely used model (also in CMUG) and might be used globally, although it is mainly suited for lakes less than 50 m deep. This is widely used by climate modellers and they might benefit from the increased availability of satellite observations of **LSWT** (already widely used), and the extinction light coefficient **k** (assessable from LWLR). **Albedo** (a) would be also an interesting parameter.
- The global lake modelling effort is also interested in **lake extent**, which has been so far derived from **Global Lake Data Base** (Version 3) since comparing ECOCLIMAP SG with ECOCLIMAP showed some inconsistency. Thus, further activities are needed: i) ECOCLIMAP SG can be used as a basic map for GLDB but the unresolved problems of miss-classification of sea and lake water must be solved; ii) similarily, some issues on endorheic lakes and some artifacts must be corrected; iii) a comparison with other candidate maps (Globcover) is shall be done.
- **Lake_cci** might offer a valuable data to Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). It is about modelling the impacts of climate change in a way that is consistent across disciplinary sectors. Such project allows comparing climate change impacts on e.g. crop yields and river flows. Currently ISMIP deals with 13 sectors, one of which is 'LAKES'. Based on ISIMIP studies, a ~9 day reduction of ice cover per °C warming was estimated, with greater sensitivity in coastal areas. ISIMIP LAKES sector considers has 62 lakes as case studies for which Lake_cci might supply data: the products of interest are **k** (and/or **Secchi disk depth**), **LSWT, LIC, LWE** and **LWL** in gridded format.
- **Lake_cci** can also help detecting ice coverage and duration (ice on/ice off) and more specifically informing when snow covers the ice (NWP purposes). Another potential sector where RS could provide inputs is the determination of inland waters salinity.

4.2. Surveys

This section illustrates the results obtained by circulating the two Lakes_cci questionnaires, the first during the initial phase of the project, the second commissioned for this document.

4.2.1. The first survey

The Lakes_cci questionnaire was composed of a brief introduction to the project and the objectives of the survey plus 12 questions. The questions were pitched generally to encourage responses by non-experts in remote sensing with interests in lakes. The survey was to climate scientists and limnologists and other potential users (e.g. water managers) generally interested in observing lakes.

The survey was promoted at the conferences that the Lakes_cci team had the opportunity to attend since the project began. The colocation CCI workshop in March 2019, and the ESA Living Planet Symposium (May, 2019) have been the key events to engage users interested to provide to us their needs via the online questionnaire. The questionnaire has been circulated widely within the scientific community by email, twitter and web. The survey was open for about two months, and was also circulated through the Climate Modelling User Group (CMUG) and of course in the Climate Research Group (CRG). The CRG also provided the indication on their needs (e.g. the lakes, region of lakes) directly to the project team. As an example, the survey has also been advertised from the home page of AquaWatch (Figure 2).

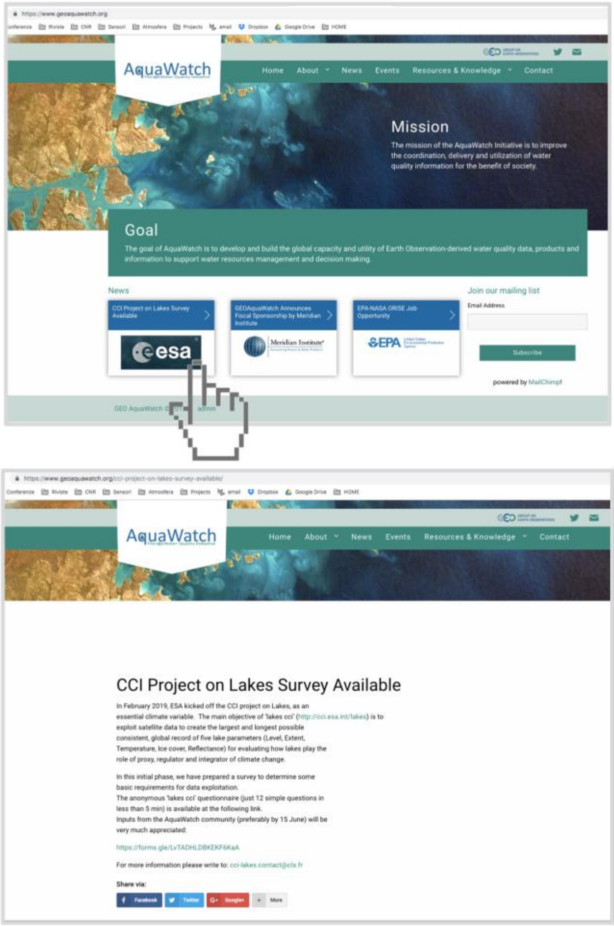
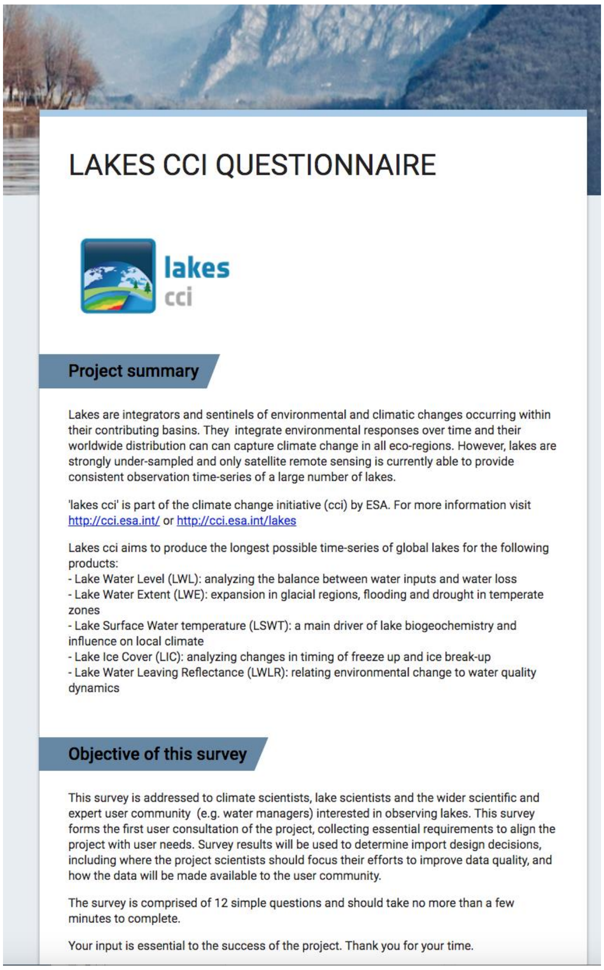


Figure 2. Link to the LAKES_CCI QUESTIONNAIRE from AquaWatch (figure taken from access performed on 17 June 19)

The first descriptive section of the questionnaire is shown in Figure 3.



LAKES CCI QUESTIONNAIRE

lakes cci

Project summary

Lakes are integrators and sentinels of environmental and climatic changes occurring within their contributing basins. They integrate environmental responses over time and their worldwide distribution can can capture climate change in all eco-regions. However, lakes are strongly under-sampled and only satellite remote sensing is currently able to provide consistent observation time-series of a large number of lakes.

'lakes cci' is part of the climate change initiative (cci) by ESA. For more information visit http://cci.esa.int/ or http://cci.esa.int/lakes

Lakes cci aims to produce the longest possible time-series of global lakes for the following products:
- Lake Water Level (LWL): analyzing the balance between water inputs and water loss
- Lake Water Extent (LWE): expansion in glacial regions, flooding and drought in temperate zones
- Lake Surface Water temperature (LSWT): a main driver of lake biogeochemistry and influence on local climate
- Lake Ice Cover (LIC): analyzing changes in timing of freeze up and ice break-up
- Lake Water Leaving Reflectance (LWLR): relating environmental change to water quality dynamics

Objective of this survey

This survey is addressed to climate scientists, lake scientists and the wider scientific and expert user community (e.g. water managers) interested in observing lakes. This survey forms the first user consultation of the project, collecting essential requirements to align the project with user needs. Survey results will be used to determine import design decisions, including where the project scientists should focus their efforts to improve data quality, and how the data will be made available to the user community.

The survey is comprised of 12 simple questions and should take no more than a few minutes to complete.

Your input is essential to the success of the project. Thank you for your time.

Figure 3. Project summary and objective of this survey reported in the LAKES_CCI QUESTIONNAIRE

The core of the Questionnaire can be summarized as follows:

- Questions characterising responders' discipline of expertise, interest in the Lakes ECV, field of applications, and linkage with other CCI variables:
    1. What are your disciplines of interest?
    2. Which of the Lakes_cci products do you need for your application?
    3. How would you use Lakes_cci products?
    4. Will you combine Lakes_cci with other CCI variables?
- Questions focused on some practical aspects of the lake data sets:
    5. For your usage, how should we aggregate the data?
    6. What factors would encourage you to use Lakes_cci products?
    7. What temporal resolution is required for your applications?
    8. What spatial aggregation is most useful for your applications?
    9. How do you prefer to download the Lakes_cci products?
    10. What is the most suitable file format for the Lakes_cci products?
    11. What uncertainty do you require from the Lakes_cci products for your application? Please specify for each variable of interest.
    12. Which cartographic reference system/projection would you prefer?

4.2.1.1. Results

There were 53 responders to the questionnaire. Some users provided us the name, institution, and e-mail address and permission for further contact for future user consultations to achieve the goals of the project. Anonymity is preserved by agreement.

The next figures provide an overview of the responses received at the time we closed the questionnaire in June 2019.

1- What are your disciplines of interest? (53 responses, not mutually exclusive)

The main disciplines of the user community are Limnology (78%) and Ecology (55%), followed by Hydrology (38%) and Climatology (32%) (Figure 4).

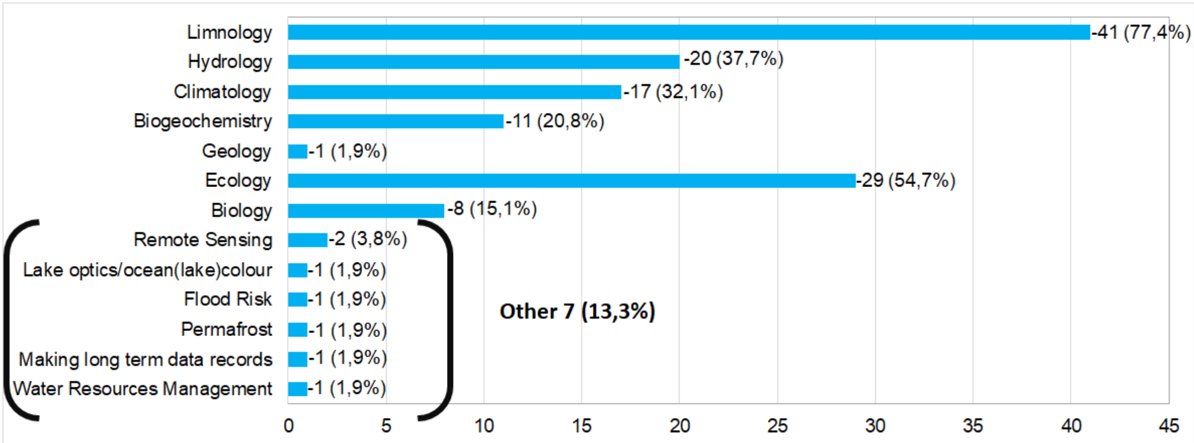


Figure 4. Histogram of answers to question 1

2- Which of the Lakes_cci products do you need for your application? (48 responses)

The first Lakes_cci variable of interest is Lake Water Leaving Reflectance (LWLR; 88%), followed by Lake Surface Water Temperature (LSWT; 75%) and Lake Water Level (LWL; 71%) (Figure 5).

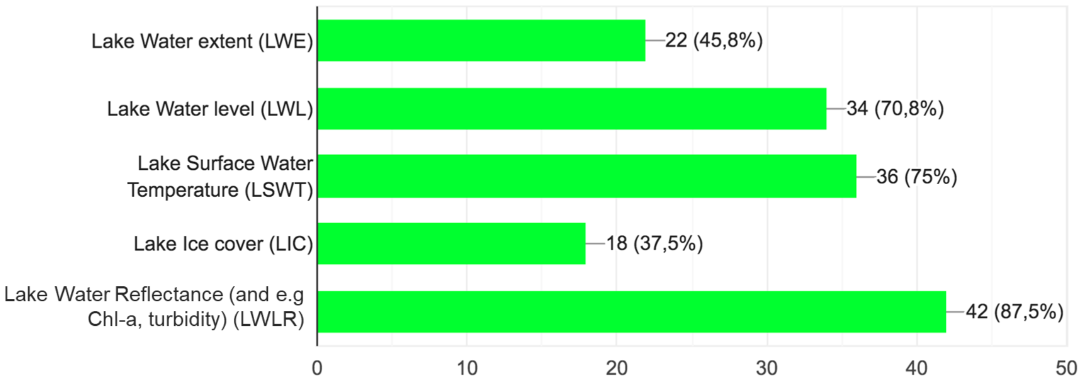


Figure 5. Histogram of answers to question 2

3- How would you use Lakes_cci products? (53 responses)

The Lakes_cci products will be mainly used for "Understanding causes of environmental changes" (76%), and for the "Assessment of trends in geostatistics" (70%), followed by "Lake management" (55%) or "Ecological modelling" (51%) fields (Figure 6).

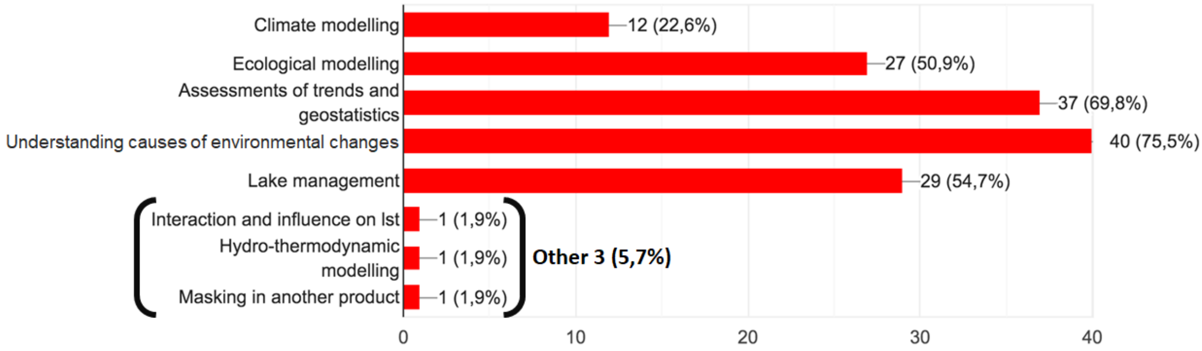


Figure 6. Histogram of answers to question 3

4- Will you combine Lakes_cci with other CCI variables (details at http://cci.esa.int/)? (53 responses)

The Lakes_cci products will be mainly connected with "Land cover" (47%) and "High resolution land cover" (30%) CCI variables (Figure 7).

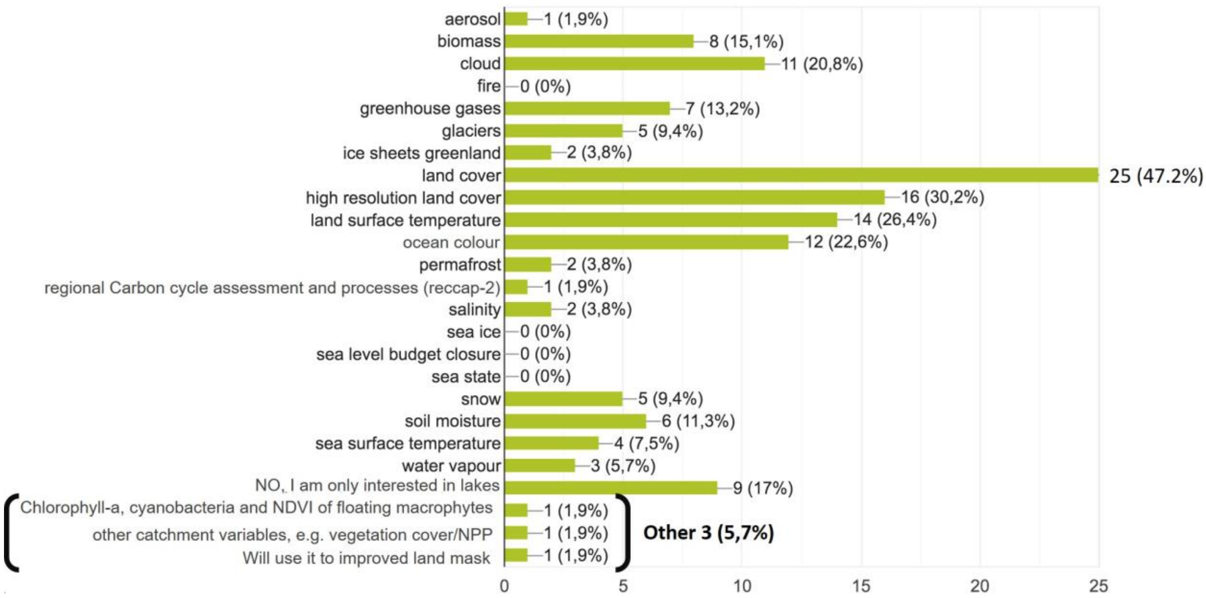


Figure 7. Histogram of answers to question 4

5- For your usage, how should we aggregate the data?

The preferred data aggregation, both for time-series and time-slices, is per single lake. This has an obvious interpretation for time-series (users who wish to study the changes in time for particular lakes of interest). It is more surprising that users require this also when accessing data one time slice at a time (Figure 8).

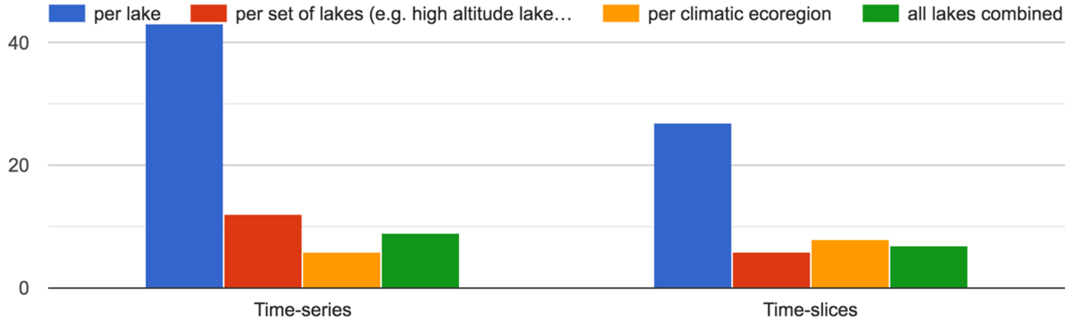


Figure 8. Histogram of answers to question 5

6- What factors would encourage you to use Lakes_cci products?

The "Easy of use", the "Length of record", and "particular lakes within the data set" are the "very useful" factors that will encourage the use of Lakes_cci products (Figure 9). The majority of users also consider the availability of uncertainty information to be either very or moderately useful (Figure 9).

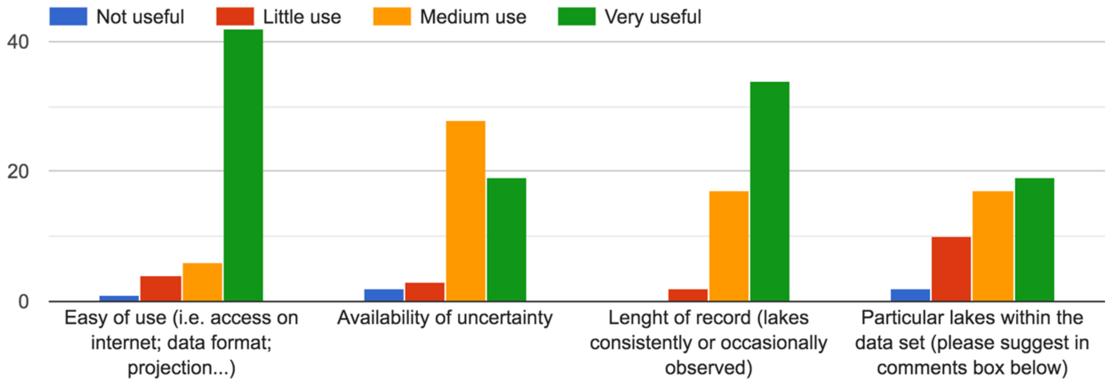


Figure 9. Histogram of answers to question 6 (the 'comments box below' indicated in the label of the fourth histogram series are those reported in section 4.2.13).

7- What temporal resolution is required for your applications?

Daily resolution is preferred for lake surface water temperature, ice cover, and water colour, while monthly data is required for water extent. Water Level data is required in equal measure weekly or monthly, followed by daily data (Figure 10).

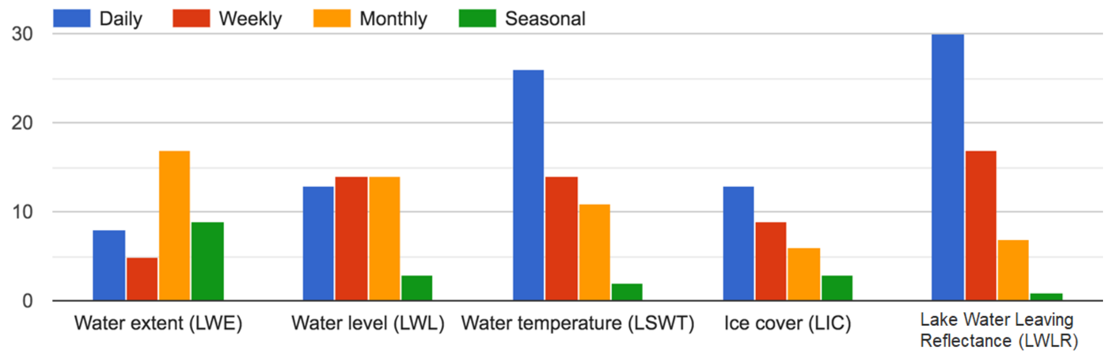


Figure 10. Histogram of answers to question 7

8- What spatial aggregation is most useful for your applications?

Spatial aggregation for water extent and level variables is required per lake (Figure 11). For LWE, this means most users' priority is the total lake area, not the information about where on the lake coastline the lake has expanded/shrunk. For LWL, the large majority of users want the lake average, reflecting the water mass balance and not interested in dynamical variations in LWL across the lake (where this available). Per pixel data is preferred for the other lake variables (LSWT, LIC, and LWLR), with an important minority in each case having an interest in only the whole-lake average (Figure 11). No interest was expressed for data aggregated per eco-region (Figure 11).

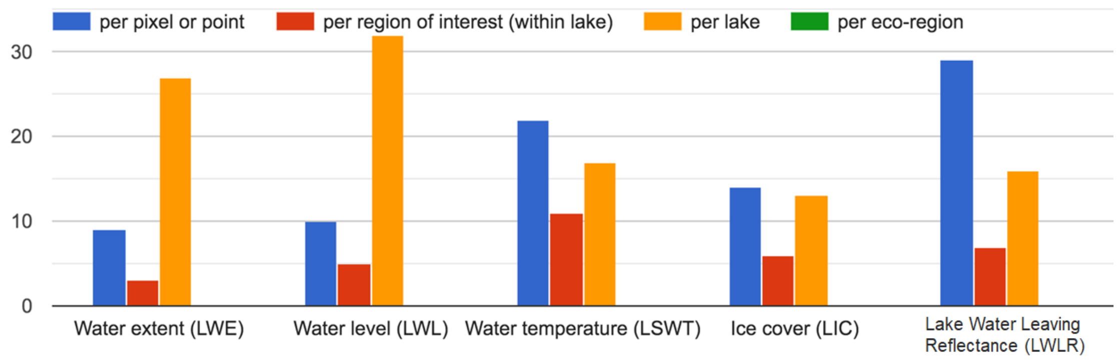


Figure 11. Histogram of answers to question 8

9- How do you prefer to download the Lakes_cci products? (47 responses)

The preferred download mode is the FTP domain (53%), followed by Web Mapping Services (WMS/Web GIS Portal; 34%) (Figure 12).

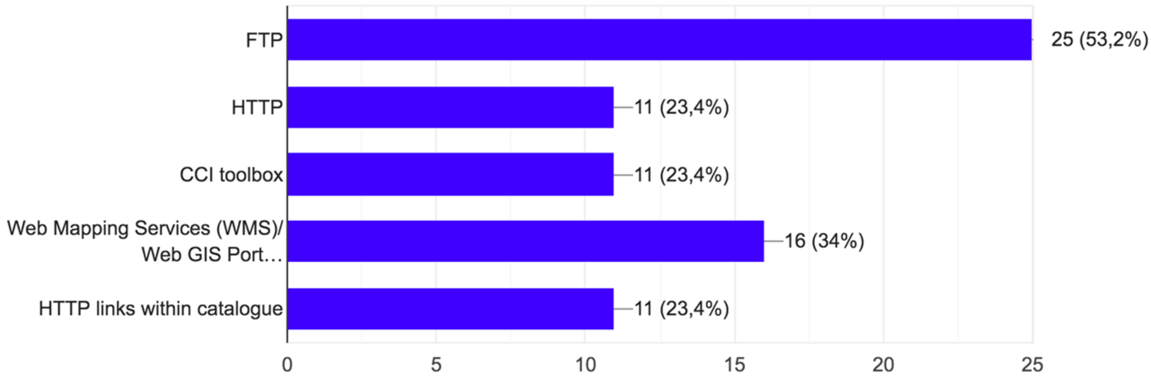


Figure 12. Histogram of answers to question 9

10- What is the most suitable file format for the Lakes_cci products? (47 responses)

NetCDF is the most suitable (51%) file format for the Lakes_cci products, followed by GEOTIFF (43%) and ASCII/CSV (40%) format. ASCII/CSV is most likely to be of use for lake-aggregated data (Figure 13).

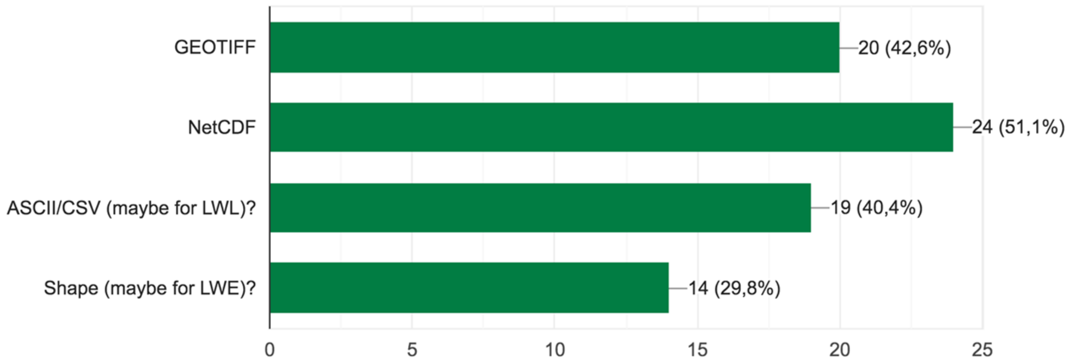


Figure 13. Histogram of answers to question 10

11- What uncertainty do you require from the Lakes_cci products for your application?

For all Lakes_cci products a good (90-80%) accuracy is required. Only for LSWT and LWLR also very good accuracy become important as second choice (Figure 14).

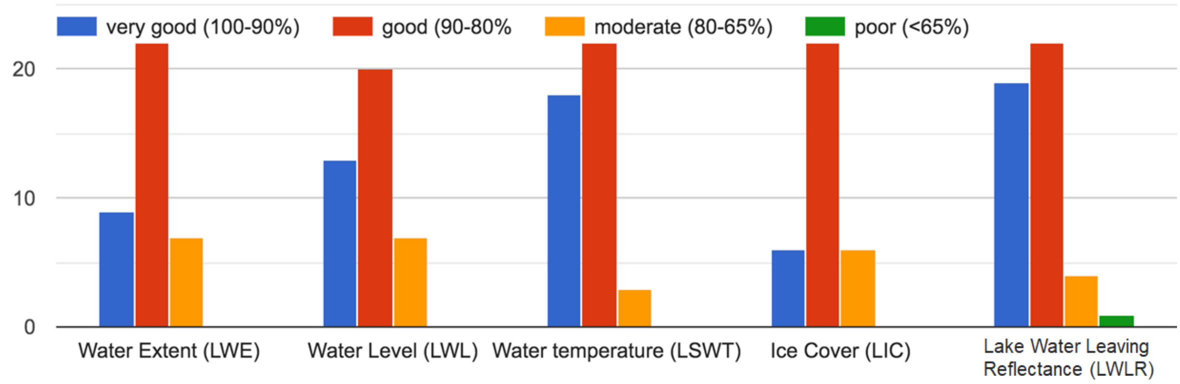


Figure 14. Histogram of answers to question 11

12- Which cartographic reference system/projection would you prefer? (46 responses)

The cartographic reference system preferred is the Lat/Long grid (70%), followed by geographic coordinate system (48%) (Figure 15).

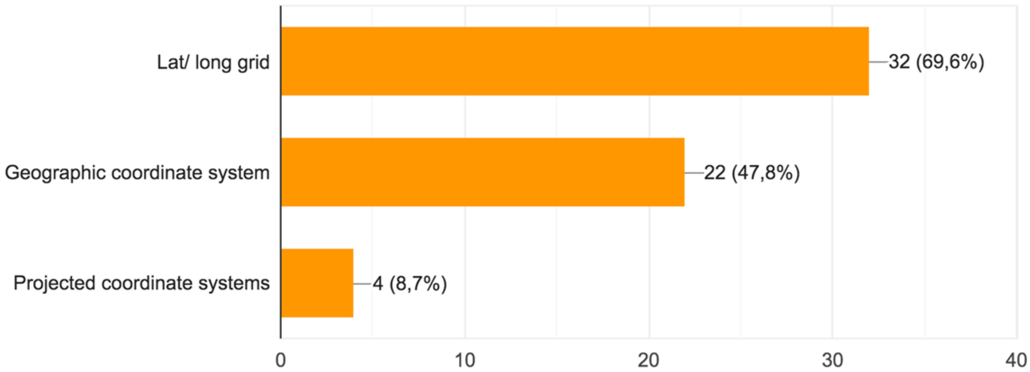


Figure 15. Histogram of answers to question 12

The user community that compiled the questionnaire added also the following comments:

- Lakes that different users regarded as of particular importance to them:
    - European and African lakes would be of particular interest
    - Subalpine lakes
    - Lakes Ohrid, Prespa, Como, Iseo, Neito (70.062386N, 70.366717 E)
- Per pixel data could be made available through Google Earth Engine
- Access to all lakes data should be organized in one place.
- Minimum useful frequency of data is monthly.

4.2.2. Second survey

The Lakes_cci questionnaire#2 (Figure 16) was composed of a brief project summary and the objectives of the survey plus 21 questions. The questions were pitched generally to provide initial feedback on the use of the Lakes CCI data (v.1). The survey was addressed to climate and lake scientists, and the wider scientific and expert user community (e.g. water managers) interested in observing lakes. This survey constitutes the second user consultation of the project, collecting feedback and requirements to align the project with user needs.

The survey was promoted internally to the Climate Research Group (CRG) involved in the use cases and to external users of the v.1 dataset. The questionnaire circulated within the scientific community by email, twitter and web. The survey was open for few months, and was also circulated through the Climate Modelling User Group (CMUG).

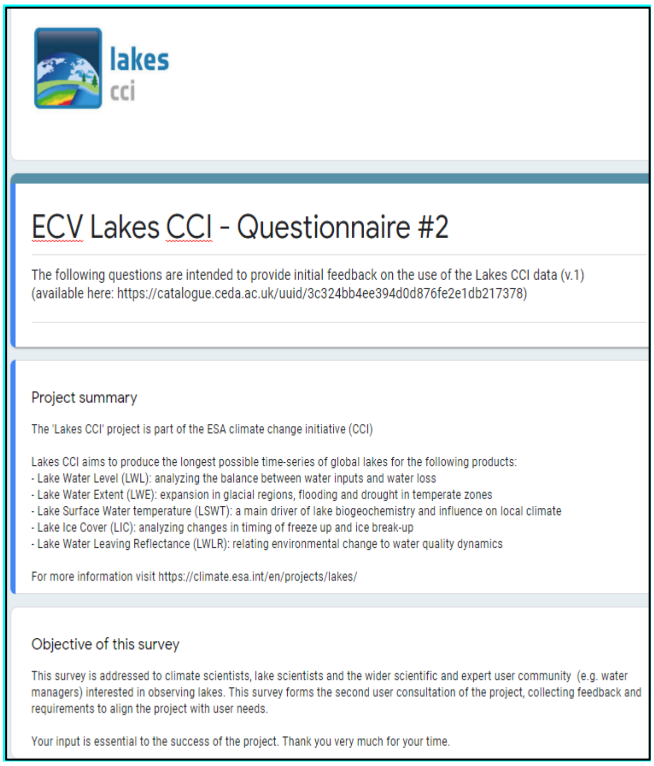


Figure 16. Project summary and objective of this survey reported in the Lakes CCI Questionnaire #2

The core of the Questionnaire #2 is summarized in the following.

A first part of the survey was composed of questions characterising responders' discipline of interest in the Lakes and information on the use of the CCI products:

1. What are your disciplines of interest?
2. Which compartment of the climate system do you investigate?
3. How did you use 'cci lakes' products?
4. Which thematic variable have you used to date?
5. Which time-range did you analyse?
6. Did you use other CCI ECVs? (If yes, why and how?)
7. Did you use any other of ESA's Climate Data Store products? (If yes, which one?)

Then the following questions focused on the feedback about the use of CRDP v.1:

8. Have you tested the CRDP dataset v.1? If yes, which methodology was used?
9. Which geographic area did you investigate?
10. When bringing together multiple datasets, what challenges do you face and how would you overcome them?

11. If you compared the products with in situ data how was the comparison? If it "Depended on lake type" please comment
12. Did you use any pre-processing of the data? If yes, specify all applied
13. What area of the lake did you analyse? Did your analysis specifically look at **spatial variation**?
14. If you encountered any issues with **data access,** what were they?
15. Did you encounter any other issues with data?
16. Please detail any **inconsistencies** noted during the analysis of the data
17. What **improvements** would you recommend?
18. Were some lakes unsuitable for use? If yes, which ones and why?
19. Do these products need a similar temporal/spatial resolution?
20. Are the interactions between other ECVs sufficient? Do they need to be improved and what tools could help communication and collaboration?
21. Other suggestions and comments

4.2.2.1. Results

The survey was specific for the users that already worked with the dataset produced (v.1 for about 250 lakes). There were 12 anonymous responses to questionnaire #2.

1. What are your disciplines of interest?

The main disciplines of interest are limnology, hydrology and climatology (Figure 17).

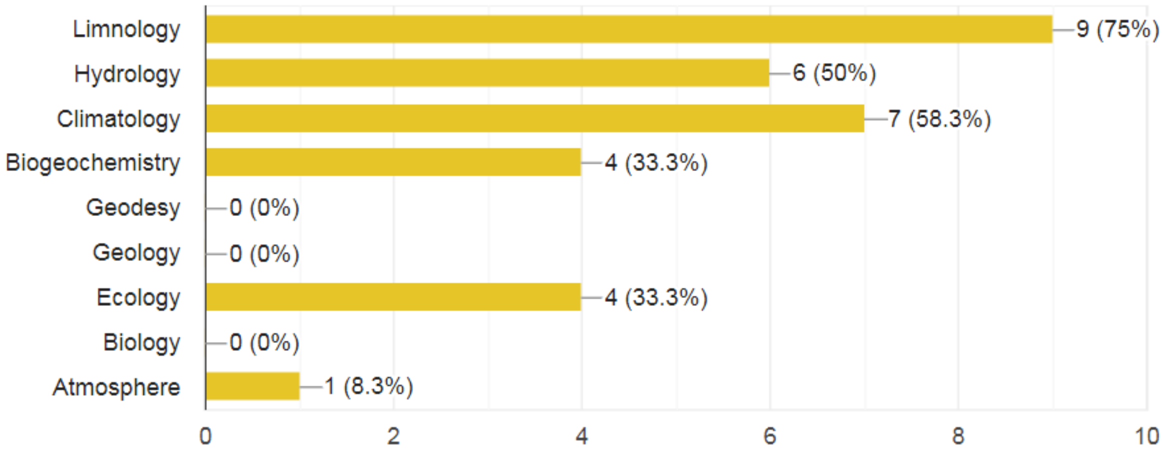


Figure 17. Histogram of answers to question 1

2. Which compartment of the climate system do you investigate?

The main compartments of investigation are related to water cycle and the interaction between land, atmosphere and ocean (Figure 18).

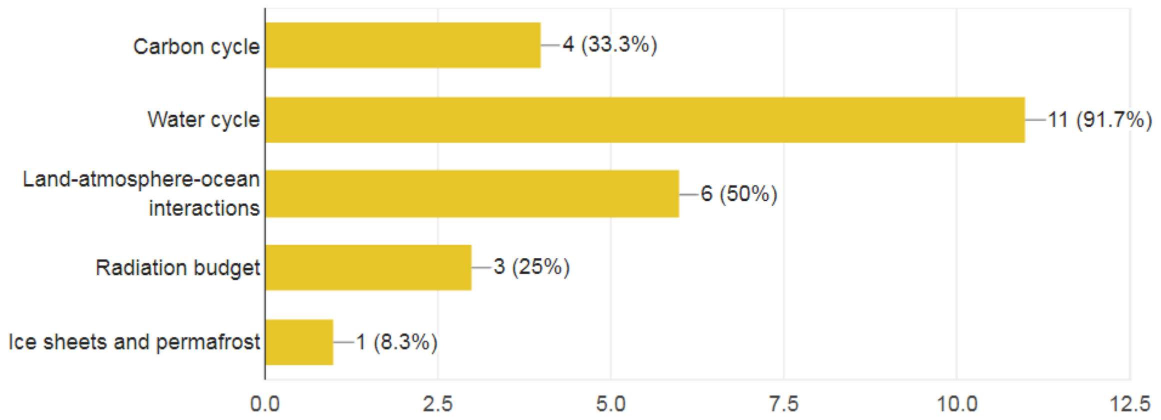


Figure 18. Histogram of answers to question 2

3. How did you use 'cci lakes' products?

The 'cci lakes' products have been used for several purposes including the assessment of trends and geostatistics, climate modelling and the understanding of environmental changes' causes (Figure 19).

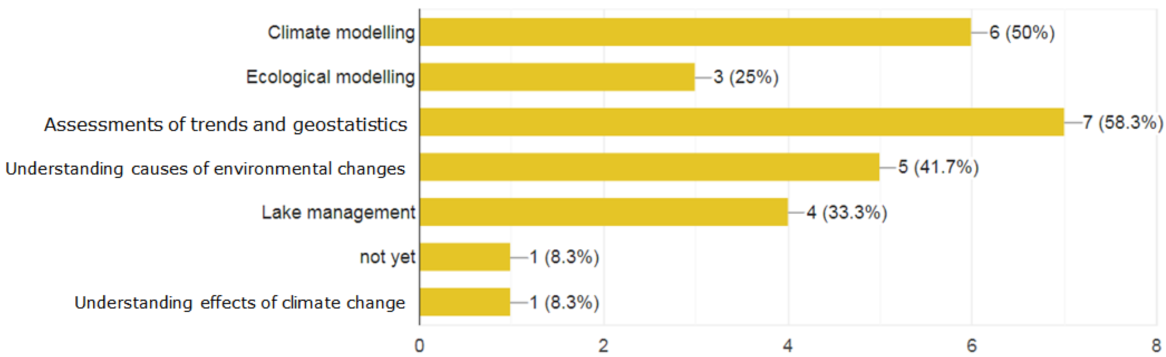


Figure 19. Histogram of answers to question 3

4. Which thematic variable have you used to date?

All the thematic variables were used, with a higher number recorded for Lakes surface water temperature data (Figure 20).

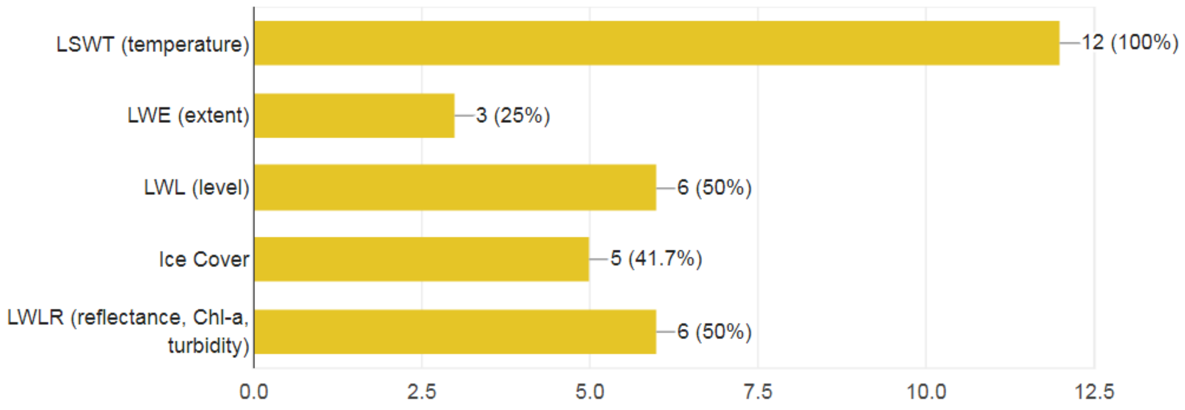


Figure 20. Histogram of answers to question 4

5. Which time-range did you analyze?

The majority of the responses highlighted the use of a dataset longer than 10 years useful for long-term studies and analyses (Figure 21).

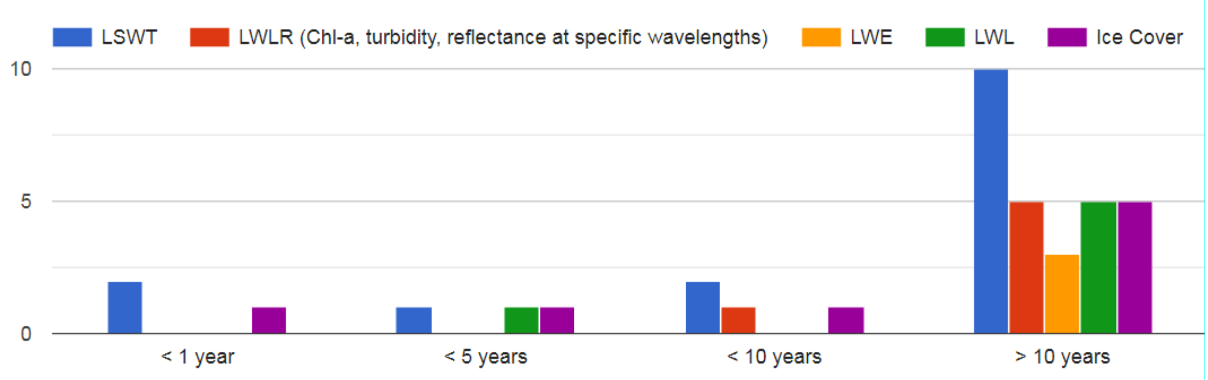


Figure 21. Histogram of answers to question 5

6. Did you use other CCI ECVs? (If yes, why and how?)

Only 4 responses were recorded for this question, and the main variables coupled to the Lakes ECVs were land cover, fire, soil moisture and water vapour. The reported aims were to monitor climate change, to evaluate climate change impacts, and to assess global and regional water cycle changes (Figure 22). Fire products were used in order to evaluate the impact of burned area to water quality and land cover ones in order to define the role in land cover change in the changing of water quality.

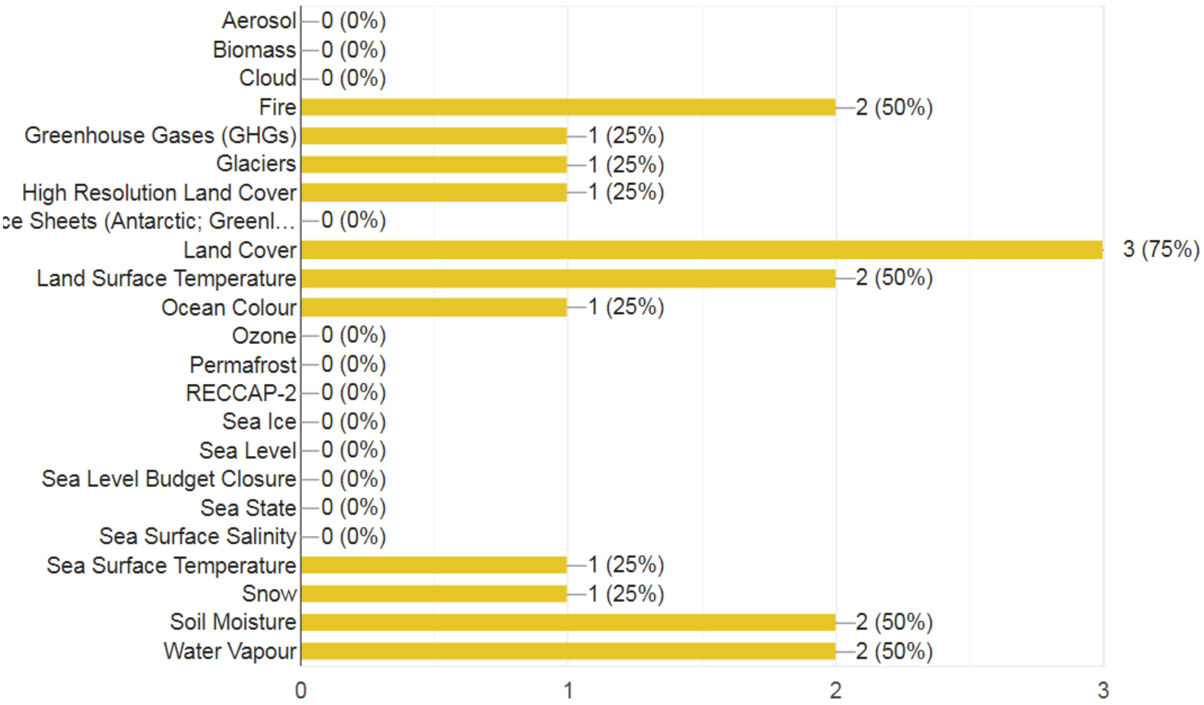


Figure 22. Histogram of answers to question 6

7. Did you use any other of ESA's Climate Data Store products? (If yes, which one?)

The 78% of the responses declared that no other ESA's Climate data store products were used. The rest of the scientists that gave a positive answer used ERA5 (climate reanalysis - wind, rain, air temperature) and ERA5-Land data, and water quantity indicators.

8. Have you tested the CRDP dataset v.1? If yes, which methodology was used?

On 6 responses only two tested the CRDP dataset v.1. On the methodology applied the answers were the following: i) downloaded from website, after trying with CATE switched to SNAP and then to R - created time series on different locations; ii) data extraction and Kendall test.

9. Which geographic area did you investigate?

On 12 responses, 2 reported global lakes, followed by continents such as Europe (2), Africa (2), East Africa (2), and Central Asia. Then Germany and Lake Constance were cited as study areas.

10. When bringing together multiple datasets, what challenges do you face and how would you overcome them?

Based on 8 answers the indicated challenges can be synthetized as follows:

i) How to do quality control for different EO data, and how to use the uncertainty product with the suggestion to have more validation to overcome this.
ii) A regular spatial grid, a stable temporal resolution (*e.g.*, different acquisition time; data gaps) and long spatial coverage.

iii) Processing, storage (*e.g.*, files very large and saved on a daily basis; make a time series of lake data) and visualization.
iv) exchange and interoperability (too much manual operations necessary), alignment of in-situ and satellite data.

11. If you compared the products with in situ data how was the comparison? If it "Depended on lake type" please comment.

The majority of the responses suggest a good/excellent relationship of satellite with in situ data (Figure 23). For the three answers "Depended on lake type" was specified that: i) worked well for some products but not for others: ii) different water quality type; iii) it's good for large lake in tropical region.

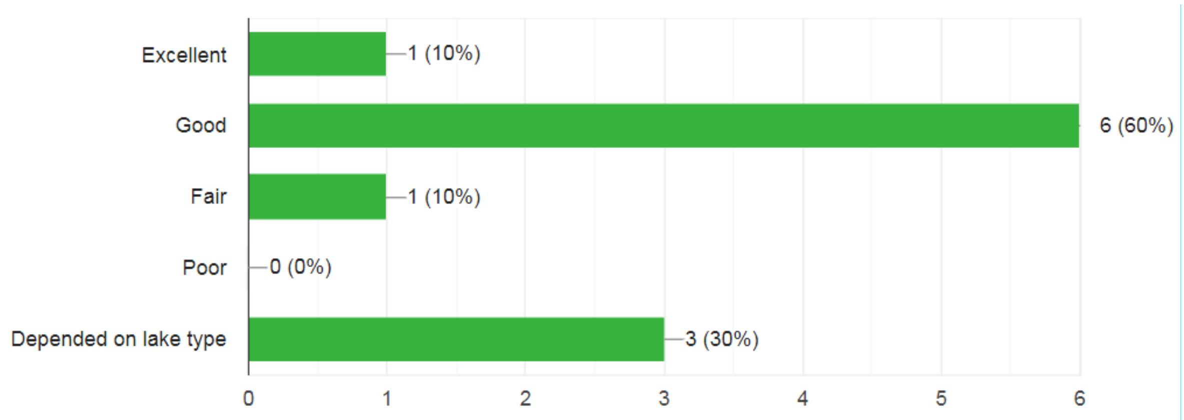


Figure 23. Histogram of answers to question 11

12. Did you use any pre-processing of the data? If yes, specify all was applied

The 64% of the responses was "yes" and the pre-processing applied on the data were reported in Figure 24.

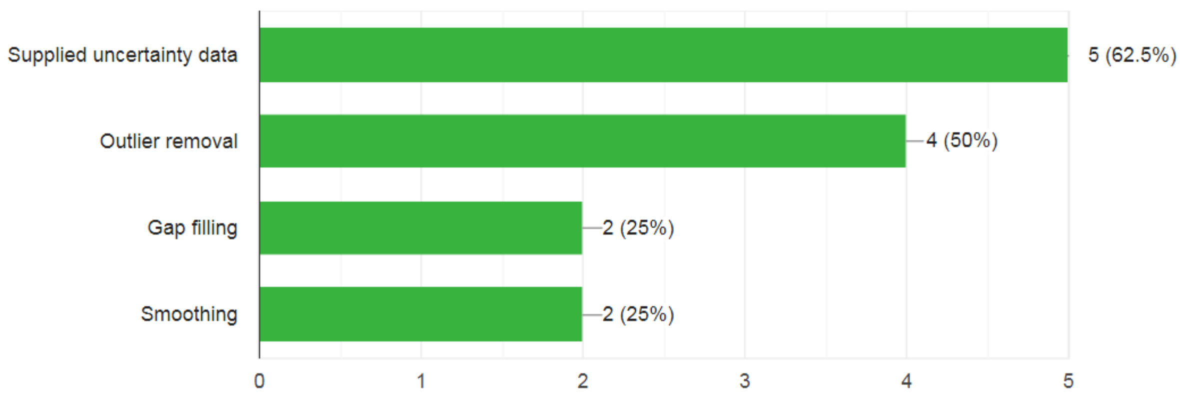


Figure 24. Histogram of answers to question 12

13. What area of the lake did you analyse? Did your analysis specifically look at spatial variation?

The whole lake is generally analysed (Figure 25), and in the 62% of the responses the target is the spatial variation.

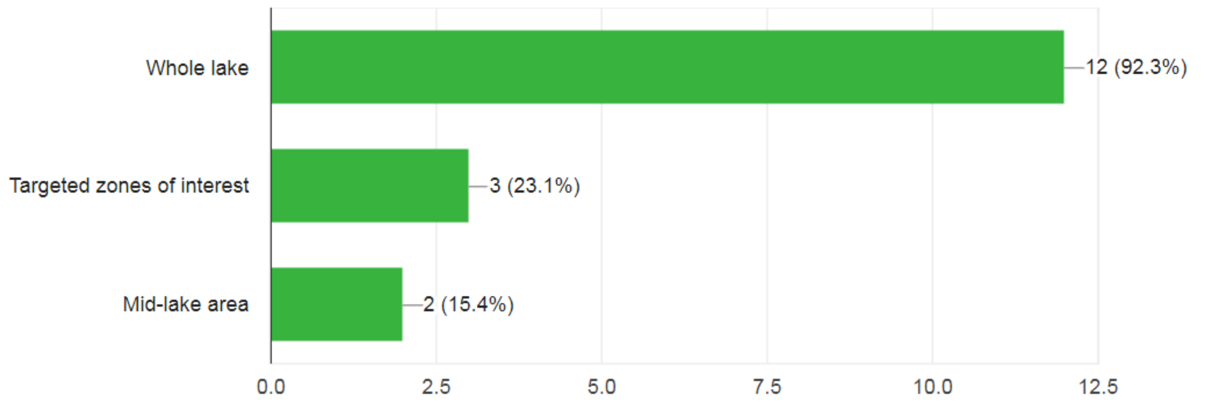


Figure 25. Histogram of answers to question 13

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

The responses to this question were reported in Figure 26. And again the format, in terms of global products or file size, is the main concern.

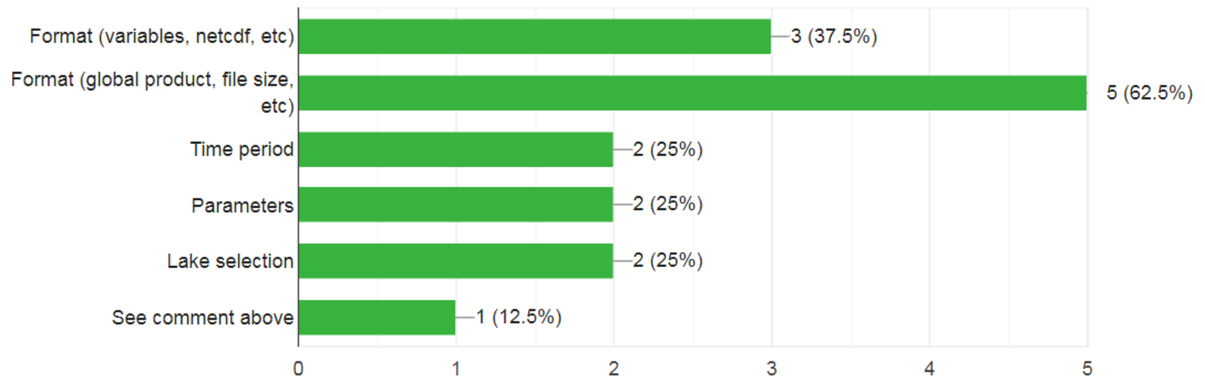


Figure 26. Histogram of answers to question 14

15. Did you encounter any other issues with data?

In general, the frequency and the accuracy of the dataset are good or satisfactory (Figure 27). The same judgement was obtained for seasonal and spatial discrepancies (Figure 27).

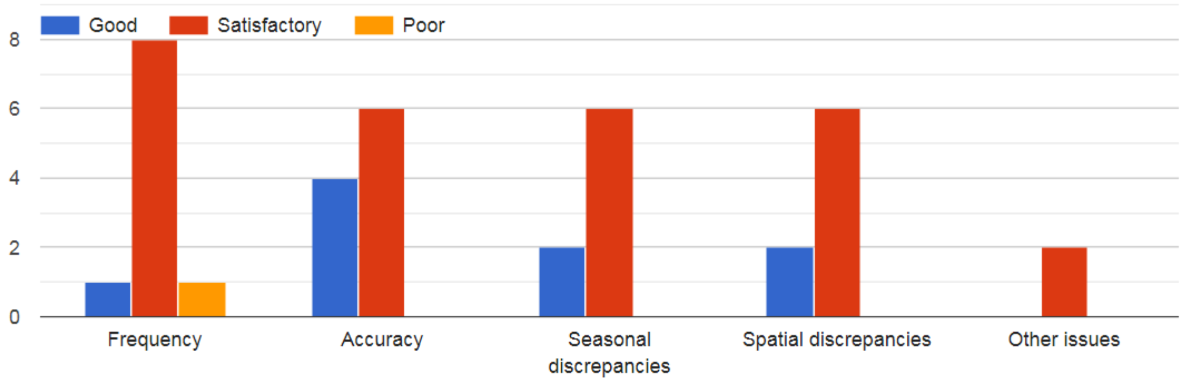


Figure 27. Histogram of answers to question 15

16. Please detail any inconsistencies noted during the analysis of the data

Only one reply was received, reporting no inconsistencies found yet.

17. What improvements would you recommend?

The two main recommendations concern the need of an increase in the number of lakes and of the frequency (Figure 28).

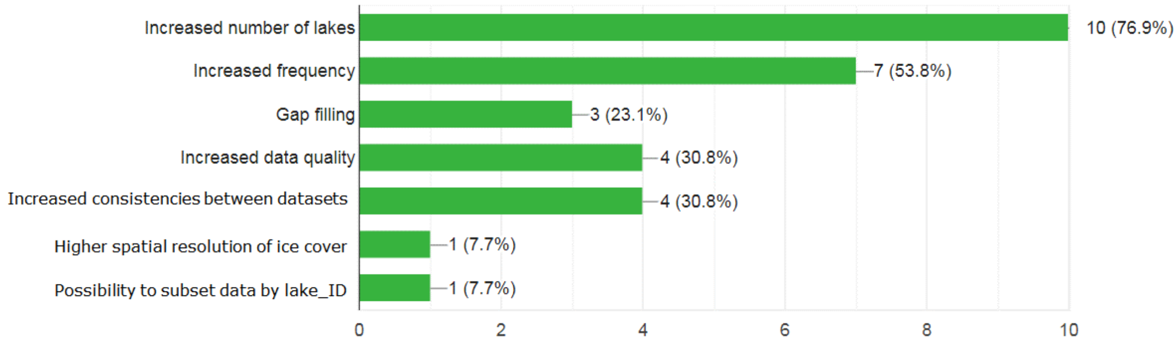


Figure 28. Histogram of answers to question 17

18. Were some lakes unsuitable for use? If yes, which ones and why?

One response suggested that a few lakes had unexplained extreme values or produced low values in some cases where very high values were certified.

19. Do these products need a similar temporal/spatial resolution?

Three different responses were produced: yes, don't know and not necessary.

20. Are the interactions between other ECVs sufficient? Do they need to be improved and what tools could help communication and collaboration?

It was suggested that a key relation can be on regional water resources and cycle, across parameters such as soil moisture, ground water levels, and runoff. Another suggestion was to make available a small RGB thumbnail images for quick viewing, in order to avoid downloading the large file first.

Finally, the other comments were the following:

i) "Without any validation, in lakes Peipsi and Võrtsjärv - the shape of the Rw looks as expected, time series of chl-a also. Spatial difference in lake is well captured (e.g. South vs North Peipsi) and between lakes (Peipsi vs Võrtsjärv). **Uncertainties are quite high, filtering results to 20% removes a lot of data**."

ii) "As representative of the ISIMIP lake sector, I can say that the ESA CCI lake data is crucial to advance climate change impact assessments. This occurs via the evaluation of the **ISIMIP lake models**. To further aid this comparison, a global coverage and long temporal coverage would be very helpful. Thank you for developing all these wonderful data sets within ESA CCI."

iii) "Would be great **to be able to clip a part of the global files before downloading to save on space and time**, similar to the Ocean Color CCI portal."

4.2.3. Summary of the two user consultations analyses

From this first user survey, we obtained some useful information about the main scientific disciplines interested in Lakes_cci' variables, which are limnology and ecology together with hydrology and climatology. Among the lake variables the major interest is towards lake water colour (LWLR), surface temperature (LSWT) and water level (LWL), while LIC and LWE are of secondary interest for the applications of the interviewed user communities. Data will be mainly used for long-term analyses on climate change causes and effects, followed by lake management and modelling. Moreover, Lakes_cci products will be mainly combined with Land_Cover_cci variables. Data access, length of record and data on particularly lakes selected by the users are very useful factors in determining the use of Lakes_cci products. Time series are preferred per lake and a good accuracy of the products is required. Lake surface water temperature, ice cover, and lake colour data is mainly required with a daily and a per pixel resolution. Spatial aggregation for lake water extent and level data is required per lake and on a monthly or monthly/weekly basis, respectively. For data access and format, the FTP domain, NetCDF format and Lat/long grid reference system are the primary choices.

From this second user survey, some information about the main scientific disciplines interested in Lakes_cci variables, which are limnology, hydrology and climatology were obtained. The main compartments of investigation are related to water cycle and the interaction between land, atmosphere and ocean. The major interest is addressed to LSWT, LWLR, and LWL followed by LIC and LWE. These variables were used for several purposes such as the assessment of trends and geostatistics, climate modelling and the understanding the causes of environmental changes. A dataset longer than 10 years was the main temporal requirement. Lakes_cci products were mainly combined with Glaciers and Land_Cover cci variables (*e.g.*, surface temperature, soil moisture, fire). At the spatial level, studies have been done on a global or continental scale (i.e., Europe, Africa and Central Asia). A good/excellent relationship of satellite with in situ data was highlighted. Few challenges were reported when using or merging dataset, such as the need of a pre-processing, of a stable temporal resolution without data gaps, and interoperability. Finally, a few concerns were related to data format (i.e., global products, file size). The need of downloading spatial and temporal portions of the dataset emerged. Further suggestions included to increase the number of lakes and the temporal frequency which might be both achieved with the second version of the CDR dataset, and the gap filling need.

4.3. Dissemination activities

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

i) attendance to conferences (*e.g.*, EGU, EO4Water; CCI Colocation, ASLO; etc.),
ii) promotion of data availability to appropriate community (*e.g.*, Lakes-CCI User Workshop; IOCCG, AquaWatch) and
iii) presentation of the project to partner network (*e.g.*, 2020-101-4-JNCC_Eo4WQ; 2020-11-17 GEO AquaWatch ARD, 2020-02-23 H2020 Water-ForCE)

A list of external conference attended by the consortium between the years 2019 and 2021 (June) is reported in Table 8.

The scope of these activities was to promote the availability of the data and receive feedback from the people attending the conferences. In different cases an interest on the data was demonstrated although the virtual conference mode did not help to go deep into the discussion.

Table 8. List of conferences, with dates, partners and type of contribution, attended by Lakes_cci consortium in the period 2019-2021 (June).

Conference	Dates		CCI Lakes Attendees	Comment
ASLO	23/02/2019	02/03/2019	C. Duguay	Oral presentation: Delivering the Lake Essential Climate Variables - an Update from ESA CCI Lakes
CCI colocation meeting	26/03/2019	28/03/2019	S. Simis/B. Coulon/C. Merchant/B. Calmettes	Poster
ESA Living Planet Symposium	13/05/2019	17/05/2019	C. Giardino (CNR)	Poster: Lakes, an Essential Climate Variable, Your Input!
9th session of the GTN-H Meeting	25/09/2019	27/09/2019	L. Zawadski/B. Calmettes	Project Presentation to GTN-H committee
SHI 2019			JF. Cretaux (LEGOS)	Oral presentation: ECV-lakes and climate change – Vision from satellites
EGU 2019	03/05/2020	08/05/2020		Abstract dead line: 15 January 2020
OSTST	21/10/2019	25/10/2019	L. Zawadski	Poster + Oral
ClimRisk19. Climate Risk: implications for ecosystem services and society, challenges, solutions	23/10/2019	25/10/2019	M. Pinardi (CNR)	Poster: Delivering the Lake Essential Climate Variable: an update from ESA CCI Lakes
Night of Ideas, Living Earth	26/02/2020	26/02/2020	JF. Cretaux	Oral presentation "Modern space technologies to understand the effects of climate change on planet Earth" Conference in French
CCI Co-location meeting	09/09/2020	11/09/2020	G. Free (CNR)	Poster: Creating the first consistent record of Lakes essential climate variables
IGARSS 2020	26/09/2020	02/10/2020	Y. Wu (H2O)	Oral presentation: Lake ice classification from MODIS TOA reflectance imagery using a

				convolutional neural network: a case study of Great Slave Lake, Canada.
GLEON 21.5	19/10/2020	22/10/2020	G. Free (CNR)	Poster and lightning talk
CLIMRISK2020: Time for action! Raising the ambition of climate action in the age of Global Emergencies	21/10/2020	23/10/2020	M. Pinardi (CNR)	Poster: Initial analysis of Essential Climate Variables from ESA's Lakes_cci Satellite Data Package
EO4Polar science	28/10/2020	30/10/2020	E. Malnes (NORCE)	
EO4Water Cycle 2020	16/11/2020	18/11/2020	LEGOS, CLS, SERTIT	
Aqua_Watch ARD	17/11/2020	17/11/2020	S. Simis (PML)	Oral presentation: Introduction to Lakes CCI and updates
10th International Shallow Lakes Conference 2021	01/05/2021	05/03/2021	M. Bresciani (CNR)	Oral presentation: Analysis of time series of the Essential Climate Variables from ESA CCI Lakes: a case study in a shallow Italian eutrophic lake
EGU 2021	19/04/2021	30/04/2021	C. Giardino, G. Free (CNR)	The essential climate variables for lakes: exploring satellite products from global to local scale
From Science to Operations for Copernicus Imaging Microwave Radiometer (CIMR) Mission	10/05/2021	12/05/2021	C. Duguay (H2O)	Oral presentation: Passive microwave retrieval of lake ice cover and thickness: advances and opportunities.
HYDROSPACE-GEOGloWS 2021 - Inland Water Storage and Runoff: Modeling, In Situ Data and Remote Sensing	07/06/2021	11/06/2021	C. Duguay (H2O)	Oral presentation: Investigating the impact of ice and snow properties on the estimation of lake ice thickness from altimetry missions.
HYDROSPACE-GEOGloWS 2021 - Inland Water Storage and Runoff: Modeling, In Situ Data and Remote Sensing	07/06/2021	11/06/2021	A. Mangilli (CLS)	Poster presentation: Retrieval of lake ice thickness from satellite altimetry missions: early results from ESA CCI+ Lakes.
HYDROSPACE-GEOGloWS 2021 - Inland Water Storage and Runoff: Modeling, In Situ Data and Remote Sensing	07/06/2021	11/06/2021	JF. Crétaux (LEGOS)/ B.Calmettes (CLS)	Validation of lake water level estimated by altimetry compared to in situ measurements
XXV AIOL conference – Italian Association of Limnology and Oceanography	30/06/2021	02/07/2021	G. Free (CNR)	Oral presentation: Detecting climate driven changes in chlorophyll-a in deep subalpine lakes using long term satellite data
XXV AIOL conference – Italian Association of Limnology and Oceanography	30/06/2021	02/07/2021	M. Bresciani (CNR)	Poster and lightning talk: Analysis of global satellite products for the Essential Climate Variable ‘Lakes’ in the LTER framework
XXV AIOL conference – Italian Association	30/06/2021	02/07/2021	M. Amadori (CNR)	Understanding lake surface transport patterns from space: opportunities and

of Limnology and Oceanography				challenges from Earth Observation and numerical modelling

4.4. Specific requirements from CRG

Within the consortium the CRG had the opportunity to answer to the on-line survey as any other anonymous responder, and to specify the lakes to be included in the satellite data production. In Table 9 the list of lakes along with thematic Lakes ECV variables is outlined; for these lakes time series is required to be as long as possible, in order to perform the activities outlined by each use case.

The use cases are focused on the following analyses:

- Use case 1: Analysis of Lakes_cci products for cold-region lakes
- Use case 2: Analysis and interpretation of ECVs for larges lakes in Europe
- Use case 3: Analysis of Lakes_cci products within the studies carried on by the international network Long Term Ecosystem Research (LTER)
- Use case 4: Analysis of brownification in Scandinavian lakes

Table 9. Details of lakes included in the four CRG use cases

Why	Name	Country	Parameters
Use case 1	Kangaarsuup Tasersua (2 lakes in total)	Greenland	LSWT, LWE
Use case 1	Nassuttuutaata tasia (2 lakes in total)	Greenland	
Use case 1	Boye So (2 lakes in total)	Greenland	
Use case 1	NN-Glacial-lakes (14 lakes in total)	Greenland	
Use case 1	Tasersuaq (2 lakes in total)	Greenland	
Use case 1	Large Tibetan lakes (17 in total)	Tibet	LSWT, LWL
Use case 2	European lakes (>500 km2)	Europe	LSWT, LWR, LIC
Use case 3	Trasimeno	Italy	LSWT, LWR, LWL, LIC
Use case 3	Erken	Sweden	
Use case 3	Iseo	Italy	
Use case 3	Kasumigaura	Japan	
Use case 3	Mendota	USA	
Use case 3	Müggelsee	Germany	
Use case 3	Taihu	China	
Use case 4	Vättern	Sweden	LWR, LIC
Use case 4	Glan	Sweden	
Use case 4	Bolmen	Sweden	
Use case 4	Oestra Ringsjoen	Sweden	
Use case 4	Rusken	Sweden	
Use case 5	Razelm Sinoe Lagoon System	Romania	LSWT, LWE LWR

Before the circulation of the questionnaire#2 to users, an internal survey was performed to have some preliminary feedback by the CRG leading the different use cases. All the variables were used (LWLR in 5 cases, followed by LSWT by 4, ice cover by 3 and LWL and LWE by one). The analyses were performed for periods longer than 10 years.

From the comparison between satellite and in situ data the following comments were reported:

- Chl-a shows a good agreement with in-situ data for eutrophic lakes, while results are less favorable at low chl-a levels or in humic lakes.
- Brownification/CDOM: due to sensor dependent differences between MERIS/OLCI, this parameter could be retrieved only for some lakes. A suitable algorithm for mapping CDOM for investigated lakes was not found yet. In situ CDOM versus FU values are similar for most of the investigated lakes.
- The LWLR products show good agreement with in situ data in turbid eutrophic lakes, and fair agreement in clear oligotrophic lakes.

Different methodologies were used for the comparison: satellite data were either extracted in specific region of interest (e.g. single pixel or 3x3 pixel) and tested against in situ measurement stations, or average values of entire lake were compared. The comparison was made for the exact day and within 3 days. The spatial analysis was performed either for the whole lake or for targeted zones of interest. Pre-processing included: outlier removal, gap filling followed by smoothing, supplied uncertainty data and averages.

The issues related to data access mainly regarded the format (file size, global product), the type of parameter, lake selection. Among these, the format issue took the longest processing time. Other issues were raised on data accuracy and on seasonal discrepancies.

Other specific comments on inconsistencies were the following:

- Inconsistency between ice products and chl-a. A lot of high values in chl-a were reported during ice cover. A mask or a post-processing solution was auspicated to avoid this issue.
- Some spatial inconsistencies (large discrepancies in nearby pixels) and temporal inconsistencies (opposed winter chl-a maxima in chl-a compared to in situ observations). For example, when trying to look at phenology changes in lake Maggiore. It was found that CCI data as it had peaks in winter chl-a inconsistent with in situ data. There were also some spatial inconsistencies observed with some pixels having a value above 100 µg/l chl-a and others below 20.
- A sensor dependent difference between MERIS and OLCI was found for smaller lakes. The affected lakes could not be used, a correction or masking of this effect was not possible yet.

The improvements recommended were the following: increased number of lakes (4 responses), increased data quality (3), increased frequency (2), increased consistency (2), and gap filling (1).

In addition, some lakes were suggested as unsuitable: i) low chl-a lakes; also applying the uncertainty filter would exclude Greenland lakes from analysis for chl-a; ii) OLCI: Bolmen, Rusken, Ivensjön, Möckeln, Vidöstern; iii) Lake Taihu (2 years of data are missing).

Other comments refer to the use case 3, where data gap were observed for example in the North American Lake Mendota between 2012 and 2015 due to the lack of suitable satellite missions. This gap might be filled with MODIS data, probably in the next version 2.0 of the products. In this use case, the CCI dataset is going to be integrated with in-situ and satellite data from LTER sites already available from previous studies. In the case of the LTER site Lake Trasimeno, the good agreement between the different datasets is suggesting that merging datasets could represent an opportunity to cover temporal data gaps.

From the use case 5, focused on consistency, an evaluation on time coverage of the lake variables was performed. More frequent data are available starting from 2009, but the major challenge for the Danube Delta area is cloud coverage, which can reduce satellite products availability by 50 % per year for LSWT, or even by 25 % per year for LWSR, in certain years.

Finally, the monthly meeting organized to present and discuss the results of each use cases to the consortium partners helped improving feedback from user needs. The updated list of 2000 lakes for product V2 considered the suggestions received, e.g. the request to include Lake Como, and LWL for LTER sites.

4.5. Requirements from the literature review

A literature review was conducted to identify well-established methodologies and requirements for the science community, which studies lakes and their role as sentinels of climate change.

It has been evident for more than a decade (e.g. Williamson et al., 2009 and Adrian et al., 2009) that climate change is generating complex responses in both natural and human ecosystems that vary in their geographic distribution, magnitude, and timing across the global landscape. Lakes are likely to serve as good sentinels for current climate change because: (1) **lake ecosystems are well defined** and are studied in a sustained fashion; (2) **lakes respond directly** to climate change and also incorporate the effects of climate driven changes occurring within the catchment; (3) **lakes integrate responses over time,** which can filter out random noise; and (4) **lakes are distributed worldwide** and, as such, **can act as sentinels in many different geographic locations and climatic regions, capturing different aspects of climate change** (e.g., rising temperature, glacier retreats, permafrost melting). However, the large range of lake morphology, catchment characteristics, and geographic locations implies caution in making broad statements about the ability of lakes to capture the effects of the current, rapidly changing climate (Adrian et al., 2009).

A substantial body of research demonstrates the sensitivity of lakes to climate and shows that **physical** (i.e. **water level, water transparency, water temperature, thermal stratification, and ice cover thickness and duration**), chemical, and biological **properties** respond rapidly to climate-related changes (ACIA 2004; Rosenzweig et al. 2007). Some climate-related signals are highly visible and easily measurable in lakes. For instance, climate-driven fluctuations in water level have been observed on a broad scale in North America (Williamson et al. 2009) and shifts in the timing of ice formation and thawing reflect climate warming at a global scale (Magnuson et al. 2000). **The criteria for choosing response variables were high synchronicity among lakes**, **ease of measurement**, **and their known relevance for ecosystem function** (Adrian et al., 2009). Not all indicators can be used broadly across all lakes, there are certain indicators that are particularly suitable for different lake types and regions. Even so, **the global distribution of lakes contributes substantially to their utility as sentinels and allows them to stand out from many other current indicators of climate change that are typically biome-specific** (e.g. the retreat of glaciers, the melting of permafrost, or the reduction in sea ice) (Adrian et al., 2009). As sentinels, lakes provide a way to detect and monitor the effects of climate change at the ecosystem scale in locations that are under-represented in climate studies or are influenced by other environmental changes.

In Table 10, we show an extract of the lake variables proposed by Adrian et al. (2009), which are of particular interest for the Lakes_cci project:

- Water temperature: **Surface** and epilimnetic **water temperatures**, which can be highly correlated with regional-scale air temperatures, **exhibit a rapid and direct response to climatic forcing**, making epilimnetic temperature a useful indicator of climate change.
- Water level **in nonregulated lakes: water level is a good indicator of climate change** because it reflects the dynamic balance between water input (precipitation,

runoff) and water loss (evaporation), and the timing of the ice-free season (ACIA 2004; Lenters et al. 2005; Van der Kamp et al. 2008) on timescales ranging from hours to centuries (Argyilan and Forman 2003; Ghanbari and Bravo 2008; Van der Kamp et al. 2008).

- Ice phenology: **The use of satellite data to study lake-ice phenology on large spatial scales enhances the utility of the timing of ice-off as a large-scale indicator of climate change** (Wynne and Lillesand 1993; Latifovic and Pouliot 2007).

Table 10. Variables useful to detect climate change responses for lakes. Advantages (A) and disadvantages (D) for each variable are also reported (extract of table 1 reported in Adrian et al., 2009)

LAKE VARIABLE	ADVANTAGE/DISADVANTAGE	REFERENCES
Water level	A: easily measured D: many lakes are regulated	Rodionov (1994); ACIA(2004); Jöhnk et al. (2004)
Epilimnetic temperature	A: easily measured D: large short-term variations; does not always correlate highly with air temperatures in small lakes	Livingstone and Dokulil (2001); O'Reilly et al.(2003); Keller (2007);Hampton et al. (2008)
Ice duration	A: integrates climate signal over longer timescale; detectable by remote sensing on large spatial scale D: if intermittent, must be observed each day	Magnuson et al. (2000); Latifovic and Pouliot (2007)
Ice-out	A: directly influenced by meteorological forcing; spatially very coherent among different lakes over large areas; tightly related to air temperature D: definition of ice-off depends on the observer; ill-defined if the ice thaws and refreezes during winter	Magnuson et al. (2000); Latifovic and Pouliot (2007)
Secchi depth phenology	A: proved efficacy as indicator; easily measured; integrates a number of processes within the food web D: affected by trophic state	Gerten and Adrian (2000); Straile (2002); Huber et al. (2008)

Effective indicators of climate change may also be the optical characteristics that integrate physical, chemical, and biological responses (Vincent et al. 1998). One good optical metric of climate change is the intensity, duration, and timing of Clear Water Phase events. **Incident UV exposure is particularly severe in tropical regions at high elevations** (e.g. high altitude plateau of Africa and South America in the band between the Tropic of Cancer and the Tropic of Capricorn) (McKenzie et al. 2007 and reference herein), **but even in very arid high elevation tropical regions DOM concentrations may be quite high** (Rose et al., 2009), **an interesting situation that clearly needs further investigation** (Williamson et al., 2009).

By nature, **the water level in lakes, and endorheic lakes (those having no outflow) in particular (e.g. in Africa), is a sensitive sentinel of changes in hydrologic balance** induced by changing temperature and precipitation. **Polar and alpine lakes are undergoing particularly rapid climate change** (Bradley et al. 2006; Veillette et al. 2008; Mueller et al. 2009), and as such may be some of the **most sensitive sentinels of climate change**. Optical changes in UV and fluorescence in an alpine lake in the Sierra Nevada of Spain are effective sentinels of dust blown from the Sahara Desert (Mladenov et al. 2009). **Annual and perennial snowpack and glaciers in some of these high-elevation and high-latitude regions can be viewed as ''upside-down lakes''** as they play a critical role in long-term storage of drinking water for a major portion of the world's populations (Bradley et al. 2006).

Although climate warming is anticipated to be most severe in polar and alpine regions, **tropical lakes are also experiencing warming trends, and more studies are needed.** Climate also influences lakes in more temperate zones (e.g. Lake Maggiore, Manca and DeMott 2009).

A recent remote-sensing study has shown that globally, lakes are warming rapidly with ongoing climate change (Schneider and Hook, 2010). In permafrost regions, such warming would not only impact thermokarst lakes as habitats but would also have profound consequences for their hydrological and morphological dynamics as well as their life cycle. In light of these possible feedback, **pan-Arctic monitoring of thermokarst lake systems in permafrost regions is needed** to assess the trajectory and magnitude of changes and **understand their consequences for the Arctic and the global system** (Grosse et al., 2013).

Sophisticated scaling and modelling approaches are required to integrate the disparate levels of response (from the use of stable isotope to the use of remote sensing and satellite imagery) of lakes to climate change at local, regional, and global scales (MacKay et al. 2009). To really understand the role of lakes as sentinels, integrators, and regulators of climate change, **broader-scale assessment of key regulating variables such as ice cover** (Mueller et al. 2009) **and CDOM** (Kutser et al. 2005) **is necessary, and techniques such as remote sensing are being successfully developed to do this. Integrating the role of lakes into global climate change will require the development of fully coupled atmosphere–land surface–lake climate models** (MacKay et al. 2009).

An alternative to "waiting" for long-term trends to develop through broad-scale networks is to take advantage of **extreme or episodic climate "events"**, such as floods, droughts, heat waves (Jentsch et al. 2007). **Space-for-time substitution studies that examine variations in lake or reservoir processes across elevation gradients or latitudinal gradients are another potentially fruitful alternative** (Weyhenmeyer and Karlsson 2009).

Duguay and Lafleur (2003) proposed **an approach to determine depth and ice thickness of shallow lakes and ponds** on a monthly basis in a sub-Arctic tundra–forest landscape (Canada) **combining Landsat Thematic Mapper (TM) and European Remote Sensing (ERS)-1 Synthetic Aperture Radar (SAR) data** (used for lake bathymetry from summertime and lakes freeze to the bottom during winter, respectively). The uncertainty of lake depth was of 15 cm (RMSE), and that of maximum ice thickness was ~1.6 m in tundra and forest-tundra zones and it was ~1.2 m in open forest zone. The approach is particularly well suited for estimating depth and ice thickness of shallow oligotrophic and ultra-oligotrophic lakes that are widespread in many regions above treeline. However**, the results also suggest that the Landsat-based approach will require further testing and improvement if one wishes to map bathymetry for shallow lakes in which large nutrient concentrations or amounts of suspended sediments are found.**

Despite global data sets documenting surface water location and seasonality have been produced from national surveys, regional statistical analysis and satellite imagery, **the measurements of long-term changes at high resolution remains a challenge** (Pekel et al., 2016). In a recent study, Pekel et al. (2016) used three million Landsat satellite images to quantify changes in global surface water over the past 32 years at 30-metre resolution. They recorded the monthly and yearly presence of water, where the changes occurred, and the seasonality and persistence of them. **Linking this information to complementary data sets, such as satellite altimetry measurements, would produce estimates of surface water volumes, river discharge and sea-level rise. General circulation models that currently treat surface water in a simplistic fashion may benefit from the accurate location of permanent water surfaces in projects including LC_cci. Mapping long-term changes in global surface water occurrence, documenting multi-decadal trends and identifying the timing (to within a given month or year) of events such as lake expansion and retreat** or river-channel migration **provides insights into the impacts of climate change** and climate oscillation **on surface water distribution**, and concurrently captures the impacts humans have on surface water resource distribution.

Satellite remote sensing (RS) has been established as an important source of information to determine the trophic state of inland waters through the retrieval of optically active water quality parameters such as chlorophyll-a (Chl-a). However, **the use of RS techniques for assessment of the trophic state of inland waters on a global scale is hindered by the performance of retrieval algorithms over highly dynamic and complex optical properties that characterize many of these systems** (Wang et al., 2018). A new RS approach was developed by Wang et al. (2018) to assess the trophic state of global inland water bodies based on Moderate Resolution Imaging Spectroradiometer (MODIS) imagery and the Forel-Ule index (FUI). The FUI-based trophic state assessment method was developed and applied to assess the trophic states of 2058 large inland water bodies (surface area>25 km^2) distributed around the world using MODIS data from the austral and boreal summers of 2012. The results showed that FUI can be retrieved from MODIS with a considerable accuracy (92.5%, R^2=0.92), and the overall accuracy of the FUI-based trophic state assessment method is 80.0% (R^2=0.75) validated by an independent dataset. In general, the FUI calculated from new sensors, like Landsat-8 OLI and Sentinel-3 OLCI, is comparable with that from MODIS using a proper correction method for the band settings (Van der Woerd and Wernand, 2018). **With recently launched sensors such as the Landsat-8 OLI and Sentinel-2(A - B), smaller lakes can be added to the dataset to achieve more comprehensive global results.**

O'Reilly et al. (2015) synthetized in situ and satellite-derived lake data worldwide, finding the rapidly increase of lake summer surface water temperatures (global mean = 0.34°C $decade^{-1}$) between 1985 and 2009 (database incorporates lake summer surface water temperatures (LSSWT) and climate variables with point collected in situ data and satellite data with a mean size of at least 9 km^2 in 157 lakes for which there were at least 13 years of data. They reported that by integrating satellite and in situ surface water temperature trends for lakes worldwide, they were able to balance the biases inherent to each data type (for example, satellite-inferred water temperature data are generally restricted to lakes >10,000 ha omitting >90% of the world's lakes that are small and shallow; MacCallum and Merchant, 2012; Winslow et al., 2015), capturing broad spatial coverage as well as geomorphic variability across a range of lake sizes. Key drivers of surface water temperature include absorbed solar irradiance and heat exchange with the atmosphere, which is controlled by air temperature, solar radiation, humidity, **ice cover**, and wind (Edinger et al., 1968), but is also mediated by local factors such as **lake surface area and depth** (Schmid et al., 2014). **Similarly, responding lakes were broadly distributed across the globe**, indicating that lake characteristics can strongly mediate climatic effects. **The heterogeneity in surface warming rates underscores the importance of considering interactions among climate and geomorphic factors that are driving lake responses and prevents simple statements about surface water trends** (O'Reilly et al., 2015).

Michalak in a recent paper on Nature (2016) highlighted the scarcity of study of how climate will affect the occurrence of the extreme events **that relate to water quality rather than quantity**. **Investigation on how to relate water-quality extremes**, their causes, their severity or their occurrence directly **to changes in climate is a knowledge gap** (Michalak, 2016). Moreover, the tendency is that **water-quality and climate scientists work in disciplinary silos**, and each tends to have a different scale of focus, and most hydrologists and limnologists study processes in individual streams, lakes, watersheds or estuaries (Michalak, 2016). **Unlike for weather variables** such as temperature and precipitation, **no global network tracks water quality**. Existing monitoring of water quality is sparse in space and time, and site-specific. **Satellite-based observations could expand coverage, but there are no widely accepted approaches for doing so. There is even disagreement about which variables best capture water quality** (i.e. the severity of a harmful algal bloom, or the total mass of phytoplankton, or the amount of toxins, or the ecosystem and human impacts)**, because each brings a different observational challenge** (Michalak, 2016).

Michalak (2016) suggested that Future Earth (http://www.futureearth.org), which provides a research platform for global sustainability science, would be a good umbrella for developing and integrating such knowledge globally. Moreover, the Global Lake Ecosystem Network (GLEON) is creating a network of scientists and sensors that are focused on using lake metabolism as a key regulator of response to climate change (http://www.gleon.org).

Observations must capture the severity of extreme events, their impacts and key variables for assessing the links to climate change. **There will be trade-offs between specificity and coverage** (Michalak, 2016). **For example, whereas satellites might monitor some water-quality parameters and impacts globally, other key indicators such as toxin concentrations can be tracked only in situ**. A forum that can explore these challenges is the GEO (Group on Earth Observations) AquaWatch initiative (Michalak, 2016).

Although papers are not yet available, it might be relevant to also analyse the ongoing work from the NSERC Canadian LakePulse Network, a scientific initiative on/ environmental issues affecting lakes (http://lakepulse.ca). The Lake Pulse Network is a five-year programme that aims to assess the state of Canadian lakes while developing new approaches for lake monitoring and advancing basic limnological science. One of the scientific aim is to assess the health status of Canadian lakes, identify their key stressors (including emerging ones) and understand how these stressors have altered and are altering aquatic biodiversity and related biogeochemical functioning as well as the delivery of ecosystem services; The LakePulse database includes data from many sources across Canada: i) LakePulse Survey (680 lakes; measure on lakes characteristics, and biological, chemical and optical variables); ii) integration with other large databases; iii) a web-based interface will allow citizens to share their lake data. With respect to user's engagement, this project points out the **necessity of focusing on lakes for which the users (maybe be a citizen, a water authority, a lake-scientist) are interested** rather than to select the lakes randomly.

Recent studies published by Woolway and Maberly (2020) and Woolway et al., (2020, 2021a, 2021b) focused on lakes at global scale in the context of climate change.

In a review published in Nature, Woolway et al. (2020) addressed the issue of global lakes response to climate change. They investigate how the physical lake variables respond to climate change, which is one of the most severe threats to lake ecosystems. In fact, lake surface conditions, such as ice cover, surface temperature, evaporation and water level, respond dramatically to this threat, as observed in recent decades. It is expected that decreases in winter ice cover and increases in lake surface temperature will accelerate lake evaporation, leading to a decrease in lake level and surface water extent. This effect also modifies lake mixing regimes. The authors suggested that future research opportunities to improve global understanding of lake responses to climate change include enhanced observation of lake variables from space (particularly for small water bodies), improved in situ lake monitoring and the development of advanced modelling techniques to predict lake processes. Moreover, the authors reported that one effort in this direction is the ongoing ESA CCI for Lakes, with the expectation that further expansion of remotely sensed data using multiple sensors could help fill data gaps and obtain consistent observational constraints for lakes worldwide. An important aspect is the focus on maximizing the benefits of Earth observations made over the past decades, as well as developing better observational capabilities from current and prospective missions.

Woolway and Maberly (2020) focused on the estimate of the velocity of climate change in the surface of inland standing waters globally. They suggested that the forecast fragmented distribution of standing waters in a landscape will restrict redistribution, even for species with high dispersal ability, so that the negative consequences of rapid warming for freshwater species are likely to be much greater than in terrestrial and marine realms. In the work they used satellite-derived lake surface temperatures from Lakes_cci for the period from 2007 to 2018 to validate lake surface temperatures derived from ERA5.

Another recent paper by the same team (Woolway et al., 2021a) focused on lake heatwaves (periods of extreme warm lake surface water temperature) under the current climate change scenario. In fact, lake ecosystems, and the organisms that live within them, are vulnerable to temperature changes as well as to the increased occurrence of thermal extremes. Nevertheless, very little is known about lake heatwaves and how they may change under global warming. For this reason, the authors used satellite observations and a numerical model to investigate changes in lake heatwaves for hundreds of lakes worldwide from 1901 to 2099, showing that lake heatwaves will become hotter and longer by the end of the twenty-first century. Surface heatwaves are longer-lasting but less intense in deeper lakes (up to 60 metres deep) than in shallower lakes during both historic and future periods. In the context of long-term warming in lakes, these phenomena can exacerbate the effects on lake physical structure and chemical properties with repercussions on species composition by pushing aquatic species and ecosystems to the limits of their resilience, on lake biodiversity, and on ecosystem services provided by lakes. In this study, daily observations of lake surface temperature from Lakes_cci project were used for comparison with the simulated lake surface temperatures.

In a similar framework, Free et al. (2021) used chlorophyll-a data retrieved by satellite (from Lakes cci) to assess the ecological implications of higher air temperatures and altered lake mixing regimes at a regional scale (supalpine region of Northern Italy). Non-parametric multiplicative regression (NPMR) was used to visualize and understand the changes that have occurred between 2003-2018 in lakes Garda, Como, Iseo and Maggiore. In all four deep subalpine lakes a change from spring to summer chlorophyll-a maxima occurred, and this could be interpreted as a regime shift in an ecological context. The cause is probably a cascading effect from increased winter temperatures, reduced winter mixing and altered nutrient dynamics.

Finally, Woolway et al. (2021b) focused on the phenological shifts in lake stratification under climate change. They stated that despite its ecological importance, historic and future global changes in stratification phenology are unknown. To fill this knowledge gap, in this study a lake-climate model ensemble and long-term observational data were used to investigate changes in lake stratification phenology across the Northern Hemisphere from 1901 to 2099. Their model forecast a prolongation in stratification that can accelerate lake deoxygenation with subsequent effects on nutrient mineralization and phosphorus release from lake sediments. The authors used the daily observations of the variable LWST and LIC of the CCI dataset to estimate the stratification phenology of lakes situated in the Northern Hemisphere (>30°N). In this study the interest was on freshwater lakes and therefore few processing was done to remove from the list the lakes that do not correspond to this characteristic.

To sum up the most recent context of the research on Lake variables, a software named “connected papers” was used to have a visual understanding of the trends and works on our field of interest. Using the recent relevant paper of Woolway et al., (2021) titled “Lake heatwaves under climate change” it was possible to visualize and extract connected papers. In Figure 29 it is shown how different lakes variables, such as water temperature and mixing regimes, lake ice etc., are subject of recent international research studies. It is clear a growing use and interest in the data produced by satellite, such as CCI dataset, to improve long-term studies.

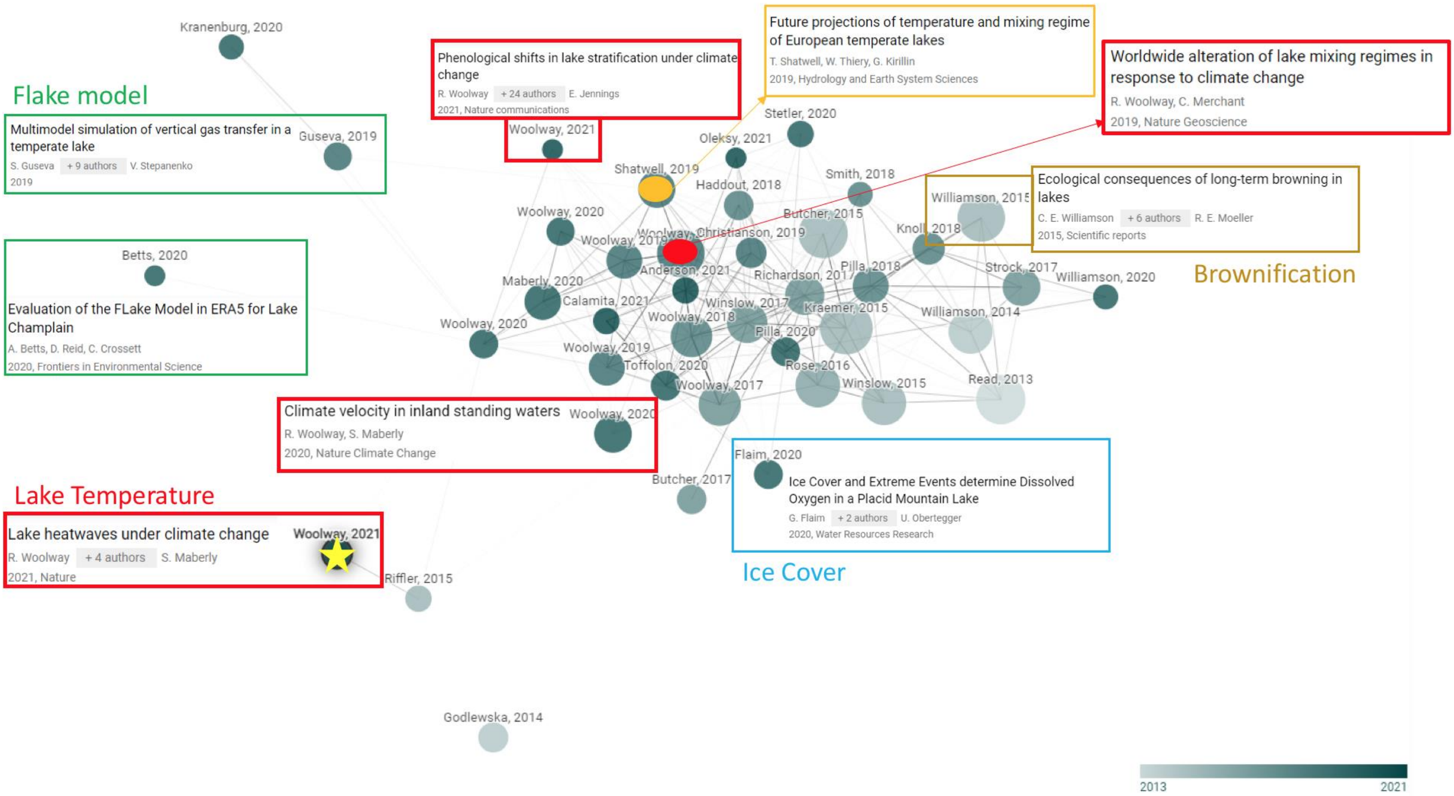


Figure 29. Recent context of the research on Lakes thematic variables (e.g., temperature, ice cover, brownification), as initialising paper Starting point: “Lake heatwaves under climate change” by Woolway et al., 2021

Then, to provide an overview of the topic and we performed a Scopus search with the following keywords, **"satellite" + "global lakes" + "climate change"**, for time range from 2019 to date. A total of 457 documents were found, with a clear increased trend in the last 3 years (Figure 30). In particular, for the period **2019-2021, a total of** 292 papers were found, featuring the recent findings on climate studies on lakes by means of satellite derived data.

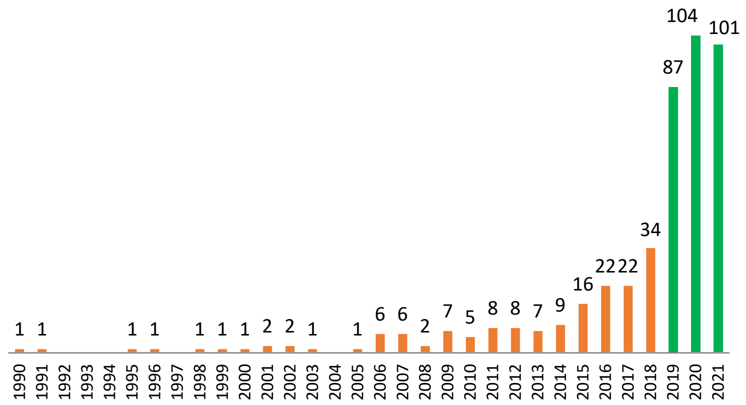


Figure 30. Published papers per year returned from Scopus search queries "satellite"+ "global lakes" + "climate change" from 1990 to date (457 documents were found). The most relevant years are indicated with green bars.

The main scientific journals in which the papers were published from 2019 to date are also reported in Figure 31(panel a) along with a brief overview of the principal countries of principal investigators (Figure 31, panel b). Form this search it can be argued how the use of satellite data for investigating climate effects on lakes is still a topic dominated by journals dealing with remote sensing that, although applications are included, are mostly devoted to algorithms developing and testing. Nonetheless key papers in high impact climate journals (9 in Nature communications) have been recently published suggesting a potential increasing trend.

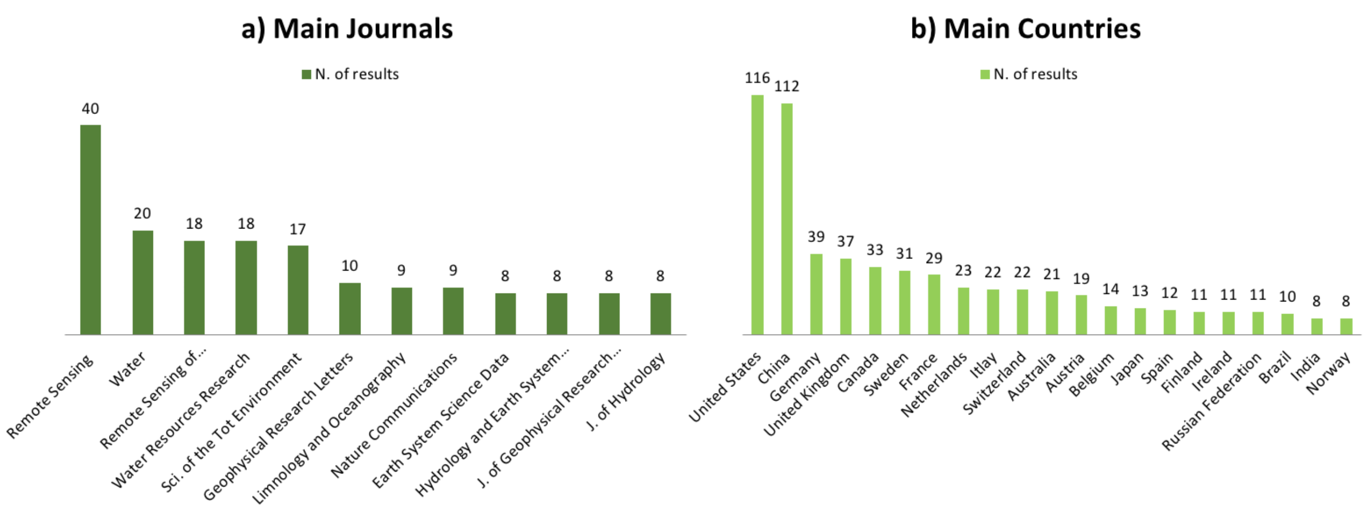


Figure 31. Distribution of publications returned from Scopus query for the main published journals for the period 2019-2021 (cf. Figure 30, green bars) (A) and the most productive countries (B).

4.5.1. Summary of requirements from the literature

Here is a list summarising the most relevant requirements that are inferred from the above literature review:

- Lakes must be monitored world-wide, so that conclusions are not dependent on biome-specific features

- There are many specific lake and lake districts that require observations depending on the application, and this is also supported by world-wide observation
- Key parameters for monitoring derived from this review are listed below. All of them have to some extent already been addressed by the GCOS definition of the ECV, albeit an additional steps is needed to link stratification to temperature and CDOM/transparency to the LSWT and LWLR, respectively):
    - water level (in non-regulated lakes)
    - water temperature
    - thermal stratification
    - ice cover thickness and duration
    - CDOM
    - water transparency
- All key ecoregions must be observed, namely: tropical (including at high elevations / very arid environments); temperate, polar, boreal, alpine
- Particularily sensitive lake types must be monitored: e.g. endorheic and thermokarst lakes
- Methods: remote sensing has been confirmed as a valuable tool for the mentioned studies adopting Lakes_cci data
- Data records need to be at least decadal and as long as possible
- A great interest and a first use of the variables LSWT and LIC at global level and of LWLR (i.e. chl-a) at regional level were found in recent papers.

5. Requirements from the Lakes_cci project

5.1. Lake Water Level (LWL)

5.1.1. User Requirement: Frequency

Following the GCOS requirement, the temporal resolution for the Lake Water Level product is daily. ***From the user's point of view, the relevant temporal resolution is equally distributed within daily, weekly and monthly***. However, the time resolution for LWL cannot be a regular one if it is only based on observations, since it is inferred from multiple satellites with different ground tracks and repeat cycles (Table 11).

Table 11. Satellite missions repetitivity

Mission	Repetitivity
Topex/Poseidon	10 days
Jason-1	10 days
Jason-2	10 days
Jason-3	10 days
ENVISAT	30-35 days
SARAL	35 days
Sentinel-3A	27 days

Summary: the frequency for LWL observations ranges from 10 to 35 days. Nevertheless, for large lakes crossed by multiple satellite groundtracks from the same or several missions, the temporal resolution can be higher.

5.1.2. User requirement: Spatial Resolution

According to the survey, the LWL average is preferable to dynamical variations across the lake. The spatial resolution could be in the Lakes_cci project considered as the minimal area for a lake to be observed. Thanks to the Sentinel3 (A and B) missions, it is however now feasible to observe a large number of small lakes not visible with historical missions.

Summary: the target spatial resolution for LWL is to estimate this value for lakes bigger than 1km^2 when they are observed by at least one of the missions. The value of 1km^2 is an arbitrary value coming from the fact that SAR measurements are presumably accurate enough to measure the water level.

5.1.3. User Requirement on Uncertainty and Stability

The most stringent uncertainty requirements for Lake Water Level comes from the monitoring of freshwater quantities. For a 500km^2 lake such as Lake Geneva (considered as a medium-to-small lake), an uncertainty of 10cm in the average water level estimation represents an uncertainty close to 0.05 Gt (5.10^7 m^3) of freshwater. As an example, this number represents the freshwater consumption of Paris over 3 months. For large lakes (typically >2000km^2), the uncertainty, following GCOS requirements, must be reduced to 3 cm. By construction, the uncertainty of the lake water level derived from altimetry is lower over large lakes: more individual measurements can be averaged, and they are proportionally less contaminated by land surface. These requirements are thus ambitious but attainable with innovative algorithms, upgraded atmospheric and ionospheric models and reprocessing as already assessed and published by several authors (Cretaux et al 2016,2018; Ricko et al 2012). For small lakes, however, the uncertainty depends on several factors (related to the lake size and shape, local environment, and geometry of the orbit). A single value valid for all lakes thus cannot be defined: from current literature and comparisons done with in situ measurements, in some cases it may reach several decimetres. It is however reasonable to achieve the requirements for small lakes when the Sentinel-3 (A and B) are used (thanks to the SAR mode). New validations are ongoing with the recent release to the project of in situ data (in the framework of cooperation with Hydrolare data centre).

These uncertainty requirements go hand in hand with the stability requirements when it comes to the study of water quantities at interannual scale. Lake Water Level variable is an integrator of the changes occurring in the watershed (in precipitation, glacier mass balance, river runoff, evaporation, etc.) and is considered as a proxy of climate change. Any changes in one of the climate conditions over the lake basin is reflected by Lake Water Level variations.

A 1cm/decade stability for the lake water level required by GCOS is realistic for large lakes but in the case of small and/or narrow lakes where satellite altimetry accuracy is poorer.

Summary: the uncertainty requirement for Lake Water Level is 3cm for large lakes (bigger than 2000 km2) and 10cm for the remainder. The stability requirement for LWL product is 1cm/decade but is currently verified only for large lakes.

5.2. Lake Water Extent (LWE)

5.2.1. User Requirement: Frequency

For the construction of the algorithm to measure the LWE product, the temporal resolution is fully related to the temporal resolution of the LWL. LWE is inferred from a combination of hypsometry and LWL products. Hypsometry is a priori validated for each lake, using a 2-D vector (LWE, LWL) obtained from a selected set of satellite images with corresponding LWL from satellite altimetry. The LWE products are then calculated when the LWL variable is produced from satellite altimetry. Therefore, the temporal resolution for LWE is controlled by the temporal resolution of LWL and ranges from a few days for large lakes to 35 days for smaller ones. Practically, with the current constellation of satellite imagers (in optical and radar) it is not realistic to estimate daily full coverage for a large number of lakes worldwide. The proposed methodology remains the most relevant and the most used in the community working on water mass detection.

Summary: the frequency for LWE depends on the frequency for LWL with observations ranging from 10 to 35 days. Nevertheless, for large lakes with multiple satellite altimetry passes, the temporal resolution can be higher.

5.2.2. User requirement: Spatial Resolution

LWE products for each lake is a single value of the total area of the lake at a given time. As for LWL, and by construction (see 5.1.2), the spatial resolution for LWE is considered as the minimal area for a lake to be observed.

Summary: the target spatial resolution for LWE is related to the LWL, which is estimated for lakes bigger than 1km^2 (see 5.1.2) when they are observed by at least one of the missions.

5.2.3. User Requirement on Uncertainty and Stability

A benchmarking activity has started in the Lakes_cci project in spring 2019, involving 4 teams of the consortium in order to estimate the most appropriate method of water mask detection over lakes in different geomorphological and environmental configurations. A few cases studies are still under analysis, but first results indicate that for large lakes (>2000 km^2) an uncertainty of better than 1% of total area is an achievable goal (GCOS requirements). For large lake, the uncertainty is driven by the accuracy of the hypsometric coefficient, which is a quantity measurable. For small lakes, it is driven by the accuracy of the LWL product, which depends on many factors and is not always measurable as explained in 5.1.3.

The most stringent uncertainty requirement comes from the linkage between water balance of a lake under climate change forcing and response of the lake extent. From theory of lake water balance widely used for the interpretation of lake storage change in time, the morphology of a lake fully drives the sensitivity of LWE and LWL, and consequently drives also the required stability for detection of trends. For shallow lakes, the most sensitive variable is LWE, which implies a lower requirement on stability than for lakes with steep bathymetry, where monitoring LWL is more convenient for identifying long term changes. A stability of 5%/decade on LWE seems a realistic objective for large shallow lakes, while it still must be verified for lakes with steep bathymetry (GCOS requirements).

Summary: Big attention is paid on this question within the project and first results are very encouraging that GCOS requirements for LWE uncertainty (10% for large lake and 5% for small ones) is a realistic objective. For stability requirement, 5% / decade is partially verified for large shallow lakes and seems a realistic goal.

5.3. Lake Surface Water Temperature (LSWT)

5.3.1. User Requirement: Frequency

The project team has been involved in studies considering the onset and end of lake thermal stratification, temperature extrema, inter-annual variability of temperature, etc. The most demanding requirement for frequency of observation relates to identifying the thermal stratification period of lakes and other “lake phenological” signals, such as time of peak temperature. To explore climate changes in such temporal signals, the minimum temporal frequency requirement is weekly observation, and the target temporal frequency requirement is daily resolution.

Summary: the target frequency for LSWT observation is daily.

5.3.2. User requirement: Spatial Resolution

The project team has been involved in studies considering the spatial variability of the onset of stratification in large lakes and the thermal contrasts between coastal and offshore waters. The most demanding requirement for spatial resolution comes when seeking to address these studies to medium and smaller lakes, since the resolution needs to be a small fraction (e.g. <5%) of the lake dimension. Useful work has been achieved with the present 1 km capability on hundreds of larger lakes, but a target for spatial resolution to address significant but smaller water bodies is 100 m.

Summary: the target spatial resolution for LSWT observation is 100 m.

5.3.3. User Requirements on Uncertainty and Stability

The most stringent uncertainty requirement comes from studies of thermal contrast (differences) where contrasts of order 1 K and more need to be measured with “adequate” uncertainty (e.g. to 20%). This implies a target for LSWT uncertainty of 0.15 K.

The most stringent requirement on observational stability comes from comparing seasonal temperatures across decades. A key research question is how LSWT decadal variability/trends compare with decadal variability/trends in air temperature (is LSWT tracking, attenuating or amplifying the climatic driver?). This means differencing LSWT trends from mean air temperature trends that are locally of order 1 K/decade. The scientific requirement here is sensitive, such as 10% in the trend, thus suggesting a target for LSWT stability of order 0.07 K/decade.

Summary: the target uncertainty for LSWT observations is 0.15 K, and the target stability for LSWT observations is 0.07 K/decade.

5.4. Lake Ice Cover (LIC)

5.4.1. User Requirement: Frequency

For climate studies, the most demanding requirement for frequency of observation relates to identifying ice dates at the beginning and at the end of the freeze-up and break-up periods, and ice cover duration. To explore the response of LIC to climate change, the minimum temporal frequency requirement is 2-3 days, and the target temporal frequency requirement is daily resolution as per GCOS and user requirements. For weather forecasting and climate modelling, fractional ice cover extent (or lake-wide ice concentration) is needed with a minimum frequency requirement of weekly observation, and the target temporal frequency requirement is daily resolution.

Summary: the target frequency for LIC observation is daily.

5.4.2. User requirement: Spatial Resolution

The project team has been involved in studies that consider the spatial variability and temporal coherence of ice dates over many lake regions using coarse-resolution passive microwave observations (5-25 km grids) through radars and optical satellite observations at ca. 10-1000 m resolution. Passive microwave observations are suitable for the study of only the largest lakes of the Northern Hemisphere. Useful results have been achieved with satellite observations at 250-1000 m (e.g. MODIS, AVHRR) on medium to large size lakes, but in order to include smaller water bodies, the target resolution is 100 m for most lake regions. This excludes some of the small (shallow) lakes underlain by permafrost. In these regions, a significant fraction of the landscape can be occupied by such lakes, for whom a target spatial resolution of 30 m would be more appropriate. However, such resolution is currently not achievable at either the temporal resolution (daily) or the length of historical record (ca. 20 years or more) required for climate monitoring.

Summary: the target spatial resolution for LIC observation is 100 m.

5.4.3. User Requirement on Uncertainty and Stability

The measurement uncertainty in LIC retrieval (10% as per GCOS requirements) has not been evaluated in previous studies. LIC products (V1 from this project) and from NASA (Snowmap) are currently being assessed and cross-compared by the team. Initial assessment performed using 17 lakes distributed across the Northern Hemisphere reveal an accuracy of 91.7% in the detection of ice cover for V1 algorithm compared to 74.6% for the NASA Snowmap algorithm. The target uncertainty of 10% set by GCOS is therefore achievable.

The most stringent requirement on observational stability comes from comparing ice cover variability and derived ice phenology (dates and duration) across decades. Key research questions are: 1) how sensitive are variability/trends in LIC to decadal variability/trends in air temperature (and the thermal regime of lakes) and how is regional climate and weather affected by seasonal and decadal changes in ice cover concentration in lake-rich regions (e.g. thermal moderation effect and lake-effect snow). A target stability of 1%/decade is required to address such research questions robustly.

Summary: the target uncertainty for LIC observations is 10%, and the target stability for LIC observations is 1%/decade.

5.5. Lake Ice Thickness (LIT)

5.5.1. User Requirement: Frequency

The most demanding requirement for frequency of observation relates to identifying maximum ice thickness (and its timing) since it is this parameter that has been most widely used in climate studies (e.g. Korhonen, 2006; Vuglinsky and Valatin, 2018; Derksen et al., 2019). To investigate the response of LIT to climate change, the minimum temporal frequency requirement is monthly observation (GCOS requirements), but should be more frequent whenever possible to determine more precisely the date of maximum LIT.

Summary: the target frequency for LIT observations is weekly.

5.5.2. User requirement: Spatial Resolution

The project team has been involved in studies that consider the spatial variability of LIT using MODIS lake (ice/snow) surface temperature combined with a 1-D thermodynamic lake ice model (1 km; Kheyrollah Pour et al., 2017) and coarse-resolution passive microwave observations (AMSR-E 18.7 GHz V-pol interpolated onto a 10 km grid; Kang et al., 2014). Beckers et al. (2017) used CryoSat-2 SARIN mode data provided at a sampling frequency of 20 Hz (~300 m) along track, averaged over a 10-km distance (mean waveform), for the retrieval of LIT over Great Slave Lake and Great Bear Lake (Canada). The most demanding requirement for spatial resolution comes from assessing the impact of climate change on the ice thickness of smaller lakes (100s to 1 km^2 in size), which is in line with GCOS requirements of 100 m.

Summary: the target spatial resolution for LIT observation is 100 m.

5.5.3. User Requirement on Uncertainty and Stability

The measurement uncertainty in LIT retrieval of 1-2 cm as per GCOS requirements is possible from ground-based measurements but not from satellite observations, at least in the foreseeable future. Mean bias errors and root mean square errors (RMSE) in the range of 6-7 cm and 17-19 cm, respectively, have been reported in LIT retrievals from AMSR-E 18.7 GHz V-pol brightness temperature (Kang et al., 2014) and MODIS lake ice surface temperature (Kheyrollah Pour et al., 2017). RMSE values in the order of 25-32 cm have been noted by Beckers et al. (2017) on the retrieval of LIT using CryoSat-2 SARIN mode data.

The most stringent requirement on observational stability comes from comparing LIT variability and trends across decades in response to key atmospheric forcing (air temperature and snowfall). A key research question is how LIT decadal variability/trends compare with decadal variability/trends in both air temperature and snowfall. A target stability of 1 cm/decade is required to address such research question.

Summary: the target uncertainty for LIT observations is 5 cm, and the target stability for LIT observations is 1 cm/decade.

5.6. Lake Water Leaving Reflectance (LWLR)

5.6.1. User Requirement: Frequency

In line with the GCOS requirements, the satellite data available to derive LWLR over lakes will allow weekly observation of water in the target regions up to a weekly resolution dating back to SeaWifs (1997). In practise, cloud, snow and ice cover, in addition to satellite uptown and downlink capacity, determine the availability of the top-of-atmosphere product over unobscured water. The user survey clearly indicates a preference for daily resolution and this is increasingly achievable with recent sensors (OLCI A/B) and MERIS (2002-2012) for higher latitudes. Observable effects of climatic shifts in lakes that are of biological nature, such as phytoplankton bloom onset and duration in relation to warming (Shi et al. 2017), will require precision of 1 day to be adequately expressed in decadal time-series. There are no technical limitations to achieve this resolution in the dataset, excluding gaps where sensor observations are lacking (older records) or where observations of the water are obscured by cloud. This means that in terms of frequency and all other considerations being equal, when sensor records overlap it would be preferred to include all available observations to achieve cloud-free observations.

Summary: the target frequency for LWLR observation is daily.

5.6.2. User requirement: Spatial Resolution

The project team has been involved in the development of water quality data processing from moderate (300-1km) and high (10-60m) resolution sensors. The latter category offers reduced diagnostic potential for retrieval of coloured dissolved organic matter and chlorophyll-*a* concentrations due to broader or missing essential spectral bands. Reflectance bands correlating with scattering by suspended solids can be captured also at the higher resolution. The most demanding requirement for spatial resolution comes when seeking to include data records of medium and smaller lakes, since the resolution needs to be a small fraction (e.g. <5%) of the smallest lake dimension to be able to resolve (and subsequently mask) the influence of nearby land, which is dependent on atmospheric conditions but can be observed up to 1 km from the shoreline. Across large areas of the world there are few lakes of sufficient size to characterize climate change effects in lakes at resolutions of 1 km or coarser, while 100 m would be far more adequate. Useful work has nevertheless been achieved with the present 300 m capability on thousands of medium and large-sized lakes, but the target spatial resolution to address significant but smaller water bodies is 100 m.

Summary: the target spatial resolution for LWLR observation is 100m.

5.6.3. User Requirement on Uncertainty and Stability

The most stringent uncertainty requirement comes from studies of phytoplankton response to climate change, particularly in lakes where these changes are subtle due to low phytoplankton abundance (0-10 mg chlorophyll-a m^{-3}). Current retrieval algorithms perform poorly in this concentration range due to our inability to analytically separate dissolved organic matter, detrital and pigment absorption in blue to green wavebands. At higher phytoplankton abundance, several forms of algorithms that utilize the near infra-red to red part of the light spectrum have shown adequate performance, while uncertainty in atmospheric correction is also lower at the longer wavebands, so this range is not considered here. It is not straightforward, and practically not useful, to express the uncertainty requirement for LWLR for radiance at all wavebands, since the water-leaving radiance signal is naturally low in parts of the light spectrum, yet highly variable. Typically, a signal-to-noise ratio is 1000:1 at top-of-atmosphere is recommended for satellite sensors. A weak normalized water-leaving reflectance signal, such as found in the near-infrared in clear waters is in the order of 0.001. A 1-sigma uncertainty of 30% (twice the GCOS requirement) is then both achievable and adequate for retrieval of target substance concentrations provided that suitable retrieval algorithms are used, whereas the GCOS requirement should be comfortably met at the peak reflectance waveband.

For practical purposes, it is far more straightforward to associate uncertainty requirements with chlorophyll-a and suspended matter retrieval. To observe lake-wide change in e.g. the interannual onset of the vegetative season, corresponding per-pixel uncertainties should be <10%. This implies a target for LWLR-derived concentrations of 0.1 mg chl-a m^{-3} or 0.1 g suspended matter m^{-3}, respectively.

The most stringent requirement on observational stability comes from comparing seasonal dynamics across decades. LWLR itself (a measure of the potential to absorb solar radiation) and substance concentrations derived from the shape and amplitude of the reflectance spectrum are of interest. For example, studies into long term seasonal trends on indicators such as peak phytoplankton bloom intensity in spring or summer will need to express 1% in the decadal trend, translating to 0.0001/decade change in reflectance for a relatively clear water body at the spectral reflectance peak or 0.1 mg chl-a m^{-3} per decade at peak concentration varying around 10 mg m^{-3} for a mesotrophic lake. The requirement for suspended matter is not as stringent from a user perspective, but given that suspended matter follows similar retrieval principles, the stability requirement can be set at 0.1 g m^{-3}.

Summary: the target uncertainty for LWLR observations is 10 to 30% for peak versus low signal bands (which vary per water type). The target uncertainty for chlorophyll-*a* is 0.1 mg m^{-3} and for suspended matter it is 0.1 g m^{-3}. Target stability for LWLR is 0.0001/decade, 0.1 mg chl-a m^{-3} per decade for chlorophyll-*a* and 0.1 g m^{-3} for suspended matter.

6. Synthesis of Target Requirements

Table 12 shows observation target requirements for the Lakes ECV parameters. Uncertainty and stability are quoted on a "1-sigma" basis (different to the GCOS presentation, so values are sometimes smaller). The general method of synthesis for these targets is to adopt the most stringent well-justified statement of requirement from previous sections.

The following synthesis is therefore a statement of target requirements and does not represent a statement of what will or can be achieved.

The traceability of the contents is guaranteed by the superscripts reported in each target cell. The superscripts legend is the following:

- G: the source is GCOS (2016)
- Q: the source is the Lakes_cci questionnaire
- P: the source is the project team's experience
- L: the source is the literature review

Table 12. Synthesised observation target requirements for the Lake ECV thematic variables ("1-sigma")

Product	**Lake Water Level**	**Lake Extent (or Lake Area)**	**Lake Surface Water Temperature**	**Lake Ice Cover (LIC)**	**Lake Ice Thickness (LIT)**	**Lake Water Leaving Reflectance (or Lake Colour)**
Measurement uncertainty	1.5 cm for large lakes (G) 5 cm for the reminder (G)	5% (relative) (G) 2.5% (for 70 largest lakes) (G)	0.15°K (P)	10% (G,P)	5 cm (P)	10-30% for peak waveband vs low signal bands (P/L), 0.1 mg m^{-3} chlorophyll-a (L) and 1 g m^{-3} suspended matter.
Stability	0.5 cm/decade (G)	2.5% /decade (G)	0.07°K per decade (P)	1% /decade (G)	1 cm/decade (P)	1% /decade (G,P,L)
Spatial resolution	N/A : per lake (Q)	N/A : per lake (Q)	100 m (P)	100 m (P)	100 m (G)	100 m (P)
Temporal resolution	daily ground-based or satellite observations (G)	daily changes (G)	Daily (P)	daily observations (G,P)	Weekly observations (P)	Daily observations (Q)
Length of record	>10 years (L)	>10 years (L)	>10 years (L)	>10 years (L)	>10 years (L, P)	>10 years (L/P)
Maximum delay before availability of data (for climate users)	1 year (P)	1 year (P)	1 year (P)	1 year (P)	1 year (P)	1 year (P)

An updated version of Table 12 was included in the document CAR V1.1 where the status of the first project year achievements was reported. A definitive table is expected to be included in the last version of the CAR (V3) by the end of the Project.

Table 13 synthesises requirements on products that apply to all the variables. A primary requirement (satisfying most users) and a secondary requirement (an alternative that satisfies other users) are provided where relevant.

Table 13. Synthesised product requirements for the Lakes ECV

Aspect of products	Primary requirement	Secondary requirement
Slicing of data (Q)	Timeseries per lake	
Spatial aggregation (Q)	Per-lake value (LWE, LWL) Spatially resolved (LSWT, LIC, LWLR) Along-track values (LIT)	Per-lake value (LSWT, LIC, LIT, LWLR)
Data format (Q)	NetCDF	GEOTIFF
Access (Q)	FTP	Web mapping service
Availability of uncertainty (Q)	Required	
Projection (Q)	Regular latitude-longitude ("Level 3")	

7. Conclusions and future developments

Lakes are globally distributed and present across different climatic zones, all of which have scientific pertinence. World-wide data from projects such as from Lakes_cci are needed to fill gaps of knowledge in some regions, such as warming trends in tropical lakes, DOM concentration due to incident UV exposure in arid high elevation tropical regions, water level in endorheic lakes (e.g. in Africa, Greenland), and pan-Arctic monitoring of thermokarst lake systems in permafrost regions. A number of lake physical properties can be measured to assess the climate change, such as water level, water transparency, water temperature, thermal stratification, and ice cover thickness and duration. In particular, the following respond directly to climatic forcing: i) surface and epilimnetic water temperatures; ii) water level in nonregulated lakes, and iii) ice phenology.

User requirements have been synthesised against this background, drawing on the statements of international bodies, literature review, the experience of the project team and two user questionnaires, of which the first was circulated at the beginning of the project and the second circulated after the publication of CDR version 1.

The analysis presented in this document, and in particular the one presented as first issue (URD v1), is reflecting the needs of a broad community of users (e.g. limnologists, hydrologists and climatologists). Such heterogeneity was also reflected by answers received from the first Questionnaire. Since the project focuses on climate change, we hence worked for presenting a second version of the deliverable (URD v2) by primarily considering an analysis of requirements from the climate community. To this aim the Lakes_cci user workshop was organised jointly to the 6th workshop on Parameterization of Lakes in

Numerical Weather Prediction and Climate Modelling (Toulouse, 22-24 October 2019). The workshop was an opportunity to collect/revise the needs from an international well focused community on climate modelling.

The second survey was more focused on feedback derived by users that managed the Lakes_cci dataset V1, including the CRG. Some suggestions regarded the need of pre-processing the data (e.g. gap filling), to have the possibility to download a sub-set of the dataset both spatially and temporally, to increase frequency, and to increase in the number of lakes.

Although the first version of the Lakes_cci dataset was limited to 250 lakes and was rather limited to an external use of the dataset the Lakes_cci team and some external users had the possibility to exploit part of the data (cf. CAR, issue 2), while everyone worked hard to promote the availability to this dataset at workshops, conferences etc. in the last and in the current year. The main outcome for updating the user requirement issues concerned the need for gap-filled data (for climate modelling), to resolve inconsistency for some products, for new thematic variables (CDOM, extinction coefficient), for more lakes, and to limit the needed processing and observational expertise.

With the second version of the dataset a wider scientific community is expected to be reached, thanks to improvements in algorithms (i.e., LWE) and in spatial coverage at global level. A significantly higher number of lakes (up to 2000 lakes, as suggested also by the community) will enhance the interest from the community working on lakes. A direct collaboration with the CMUG is also planned in order to explore the possibility to perform the gap filling mainly for LSWT and LIC data.

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