Consortium Members

D5.3: User Requirement Document (URD)

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1. Executive summary

This document summarises the user requirements for the Essential Climate Variable (ECV) 'Lakes' collected within the framework of the European Space Agency's Lakes Climate Change Initiative (http://cci.esa.int/lakes) (Lakes_cci). It presents the synthesised information obtained through review of existing documents, and of publications and projects, plus a user survey of 53 respondents. A perspective to update the understanding of user requirements, more focused on climate community needs, it is also outlined in the last section.

The approach builds on a review of existing requirements that were specified both in the Statement of Work and in the Lakes_cci as those specified by the Global Climate Observing System (GCOS). Then, a new set of user requirements for Lakes_cci have been obtained through an online survey, which was open to both current and potential users of the ECV Lakes for both climate and more general applications. The survey has been widely disseminated via conferences, email, Twitter, Slack channels and online, including to the CCI Climate Modelling User Group (CMUG) and the project's Climate Research Group (CRG).

The following points of interest have arisen from this preliminary user consultation and analysis:

- In general, the observational requirements of GCOS are supported or require to be more stringent (when interpreted as targets).
- Most users prefer data to be made available as timeseries on a per-lake basis in netCDF.

2. Overview

This is an update to the first version of the User Requirements Document for ESA's 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's (ESA's) 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's Climate Change Initiative). As part of the CCI project, Lakes_cci is included in the CCI second phase, and this document provides is first issue of the user requirements document for this ECV.

Lakes are a significant interest of 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 option of Lakes_cci.

In this context, Lakes_cci represents a unique framework to provide data to the multiple 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. Including 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. Requirements obtained in interaction with user communities are reviewed in section 4. Requirements evident within the Lakes_cci project follow in section 5. These statements of requirement are inevitably varied because of their different origins, and thus in section 5 for each sub-variable within the ECV Lakes we synthesise reasoned headline requirements traced to their origins.

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)

Essential Climate Variables (ECVs) that require long-term observations, for the atmosphere, the continental surface and sub surface, and the ocean, have been defined by the Global Climate Observing System (GCOS). (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 with regard to 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 at Bali, December 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 parameters of the Lakes ECV and made ECV-specific requirements summarised in Table 2. The “Lakes ECV” comprises 5 parameters, 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 values reproduced in Table 2 for measurement uncertainty are defined by GCOS as the target uncertainty with a coverage factor of 2, which means that to obtain the requirements expressed as the standard uncertainty of the named quantity (the usual presentation), these values 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 that requires refinement, through expert and user 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 area 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. Much observational data on hydrological ECVs, such as rivers, lakes and groundwater, are not reported internationally. 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 of the hydrosphere and cryosphere but that across the terrestrial domain and between ECVs is lacking.

The GCOS (2016) identified a number of actions to improve monitoring of ECVs or 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 to improve the observations 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 sustain efforts on improving algorithms, processing chains and uncertainty assessments for these 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.

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.

Roles of CMUG including supplying requirements such as identifying water bodies and data and uncertainty requirements. CMUG will review product performance through application of CDRs to model validation and assimilation, to help to improve the requirements for each ECV and their derived components and to demonstrate the value and limitations of the products within the modelling community.

With respect to the Lakes_cci project, the first interaction with CMUG was 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 ECVs. The meeting was attended by a Science Lead and the members of CRG from each of the nine new ECV projects, and researchers from many of the existing CCI ECV projects attended as well.

With respect to the interaction between ECV projects and CMUG the meeting was developed in order to reach specific aims such as:

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

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

- Uncertainty: the same language should be used to describe uncertainties across all ECVs, with the recommendations of Merchant et al. (2017) adopted as guidelines to be consistent 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. Consistency here does not imply that all thematic variables with Lakes_cci provide data for the same set of pixels within a defined lake area (additional masking is required for most thematic variables), but the definition of the observed lake area will be consistently based on LandCover_cci.
  - a matrix (Figure 1) of CDRs that particularly require cross-ECV consistency was compiled. Green boxes indicate that the projects named on the top row have a dependency from the project names in the vertical left column, in the opinion of the CMUG.

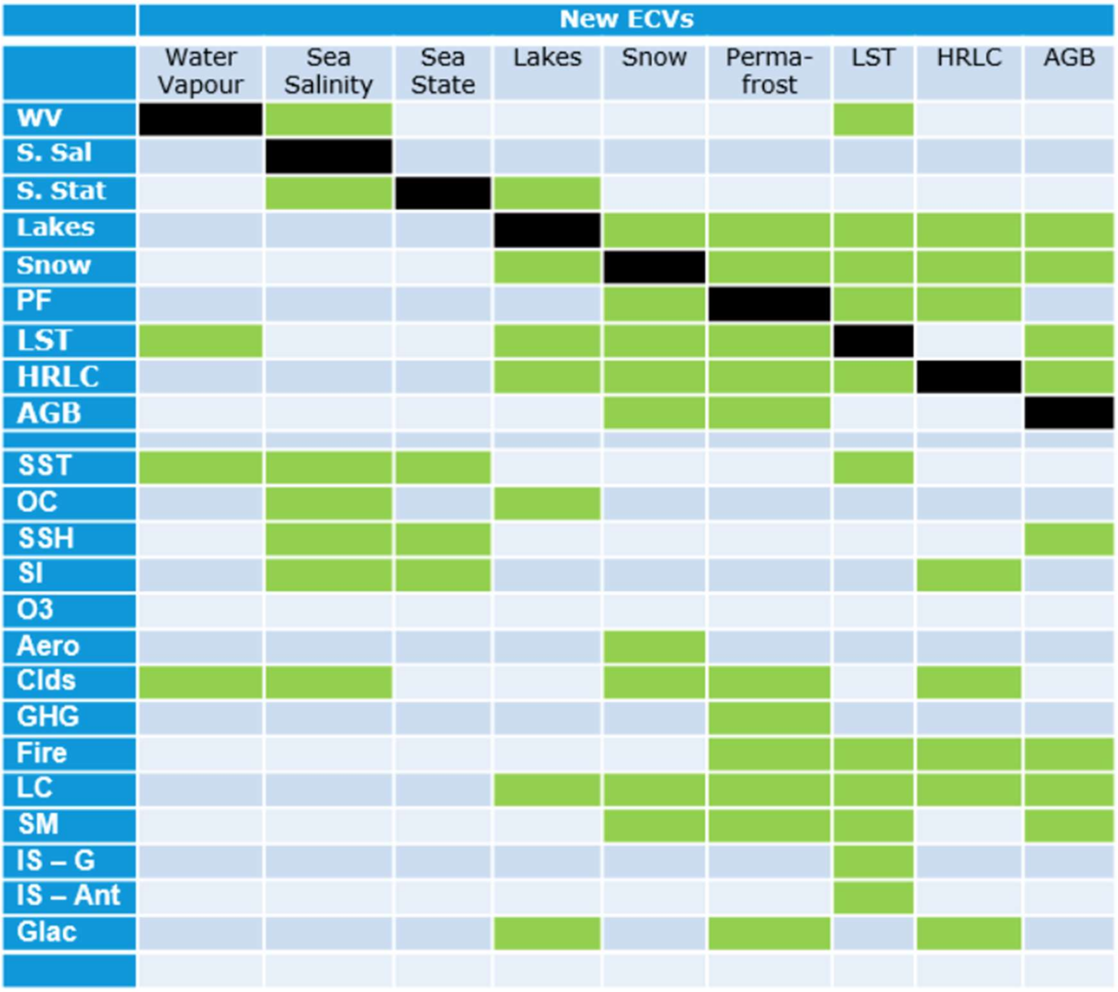


Figure 1. Dependencies between the new CCI ECV projects and all the CCI ECV projects

- 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, it was expressed the need to circulate the agenda of cci quarterly report meetings. In case CMUG see an interest in attending the meeting CMUG might ask to attend; this is a way that might be adopted by Lakes_cci to easily get and update the requirement of CMUG activities, and in particular to the one related to WP5.

4. Requirements collected by the lake community

4.1. Methodology

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).

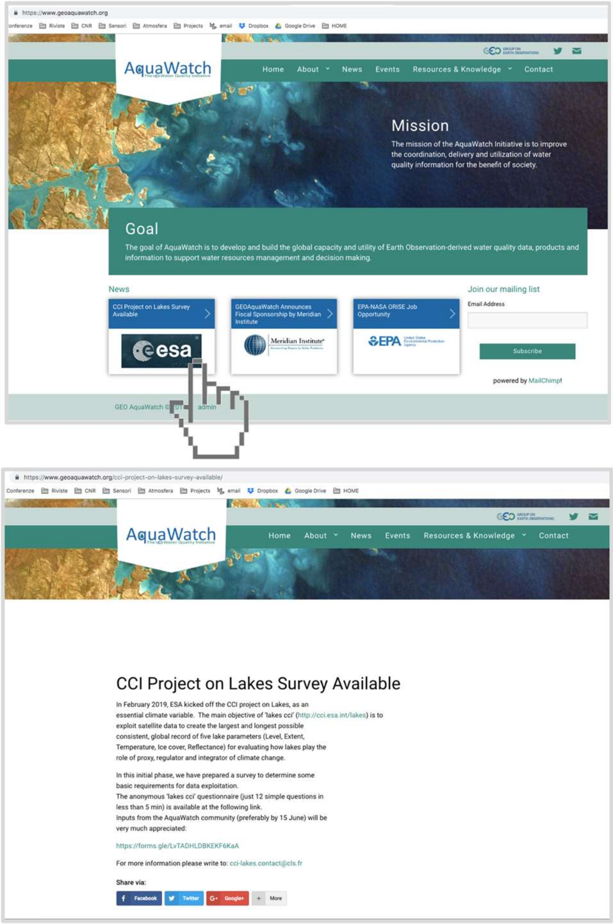
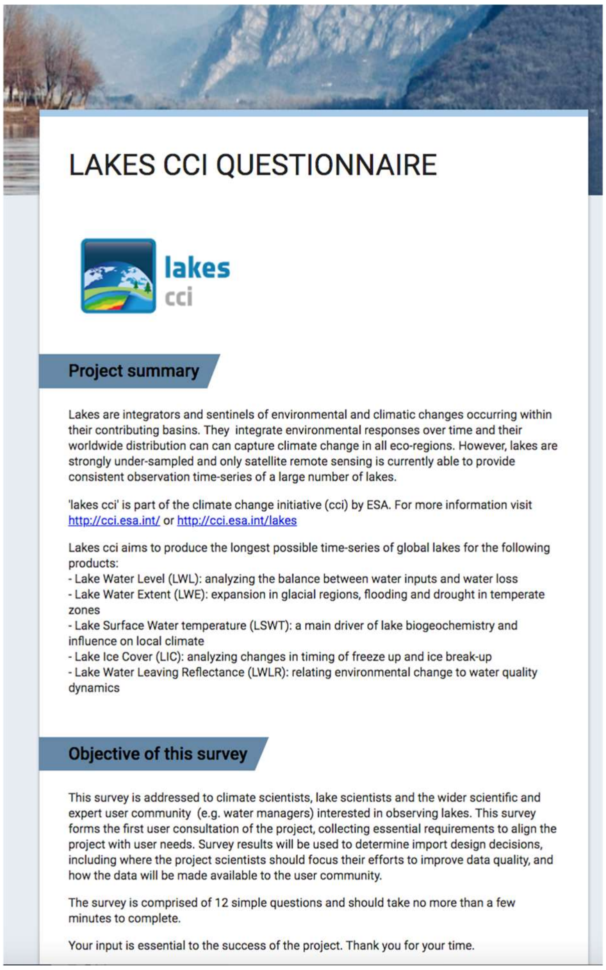


Figure 2. Link to the LAKES_CCI QUESTIONNAIRE from AquaWatch (figure taken from access performed on 17 June 19)

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. 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.

4.2.1. Expertise of responders

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).

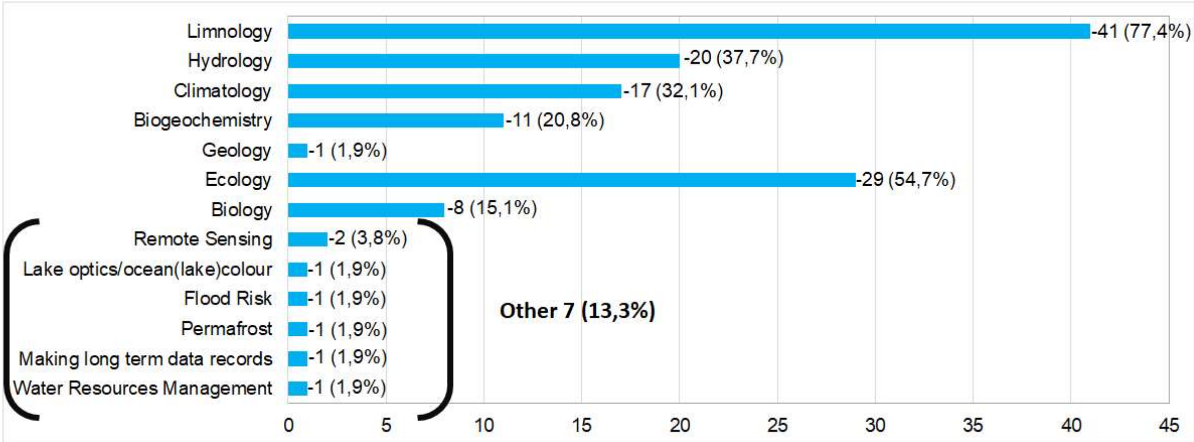


Figure 4. Histogram of answers to question 1

4.2.2. Needs for lake parameters

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).

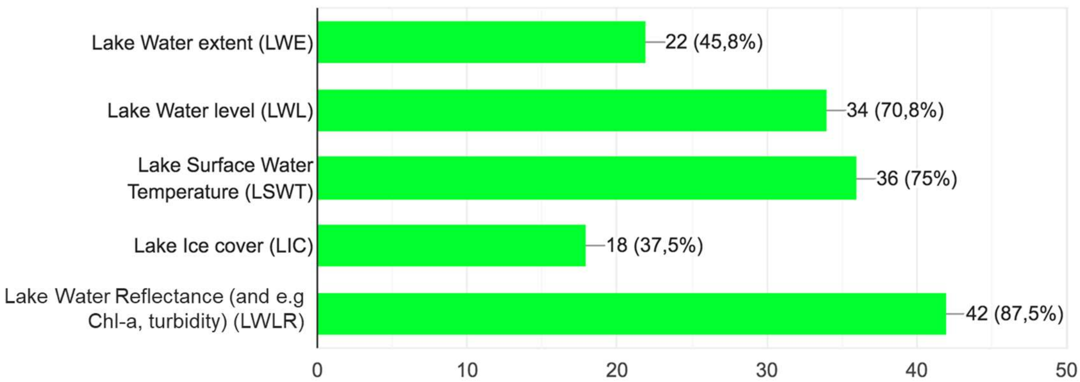


Figure 5. Histogram of answers to question 2

4.2.3. Domain of use of Lakes_cci products

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).

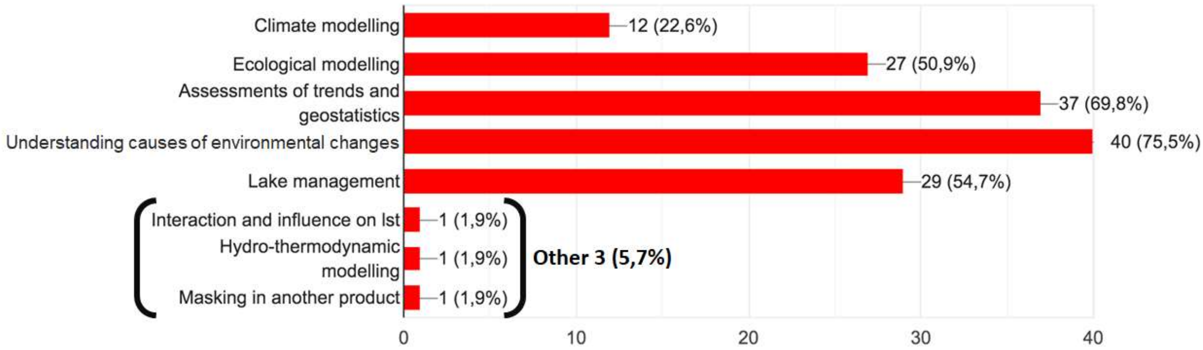


Figure 6. Histogram of answers to question 3

4.2.4. Joint use with other CCI data

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).

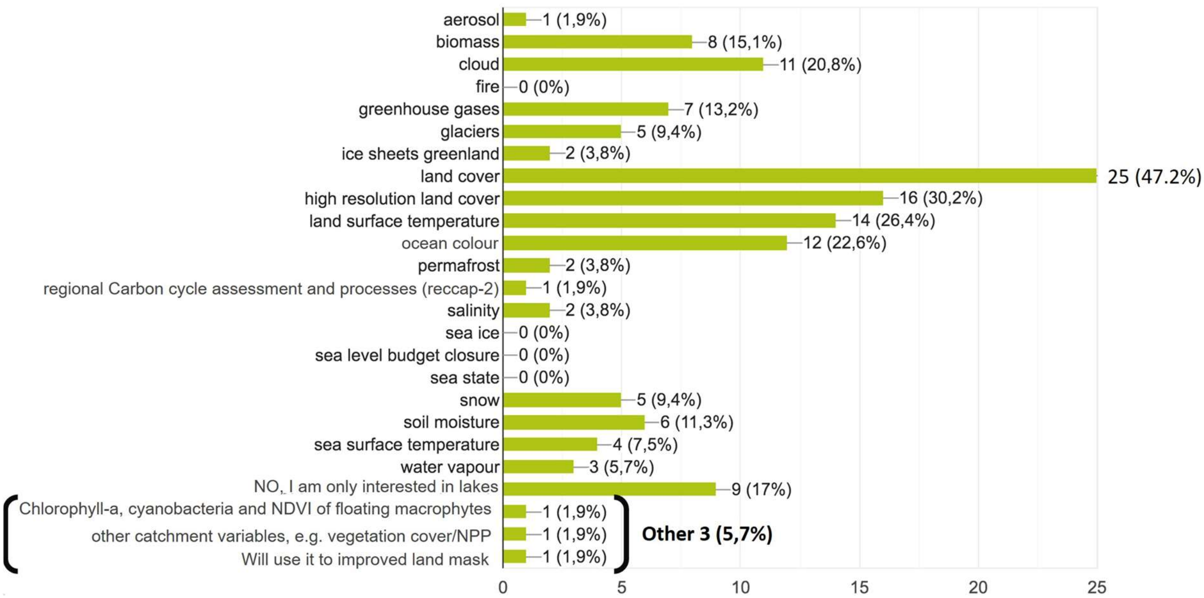


Figure 7. Histogram of answers to question 4

4.2.5. Requirements for aggregation

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).

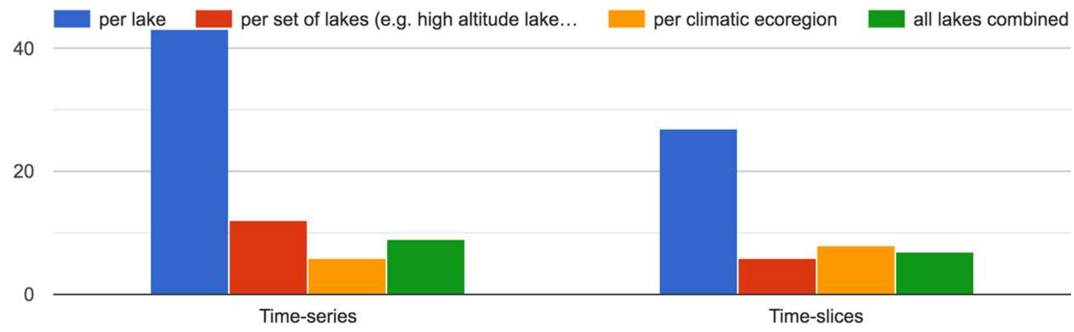


Figure 8. Histogram of answers to question 5

4.2.6. Factors encouraging uptake

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).

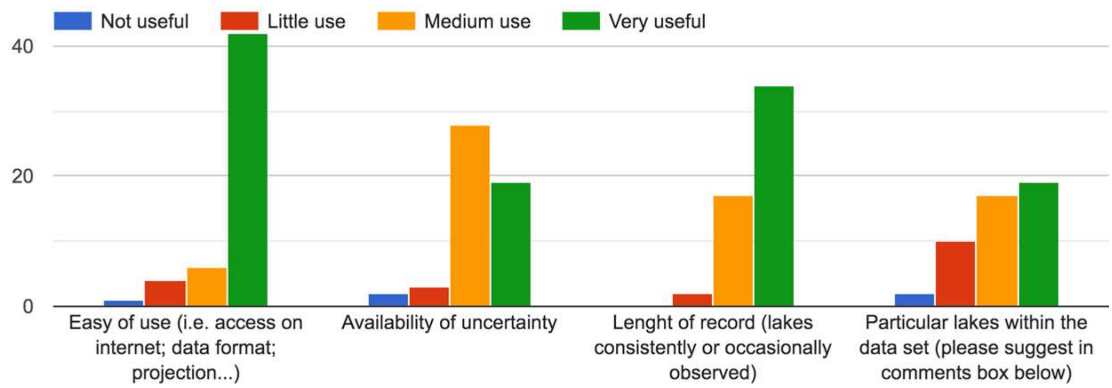


Figure 9. Histogram of answers to question 6 (the ‘comments box below’ indicated in the label of the fourth histogram series are those reported in section 4.2.13).

4.2.7. Requirements for temporal resolution

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).

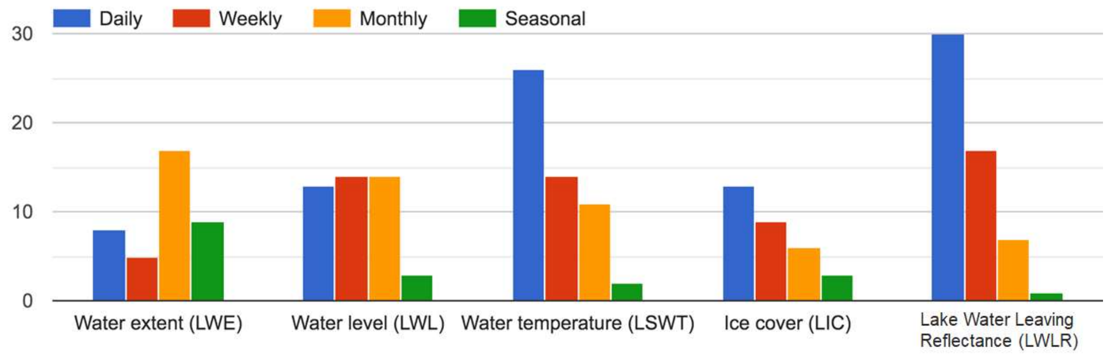


Figure 10. Histogram of answers to question 7

4.2.8. Requirements for spatial aggregation

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).

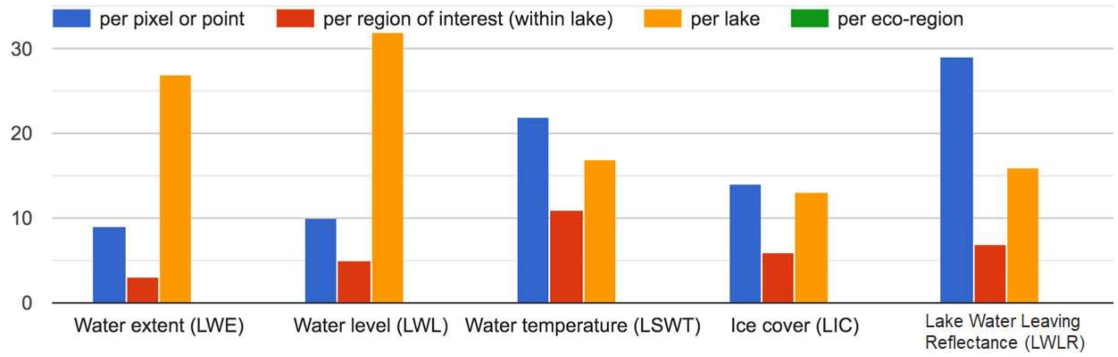


Figure 11. Histogram of answers to question 8

4.2.9. Requirements for data download

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).

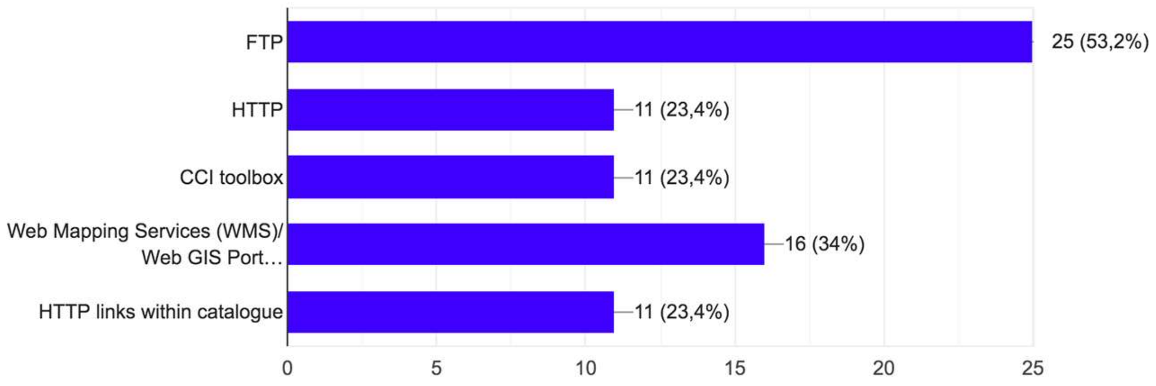


Figure 12. Histogram of answers to question 9

4.2.10. Requirements for data download

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).

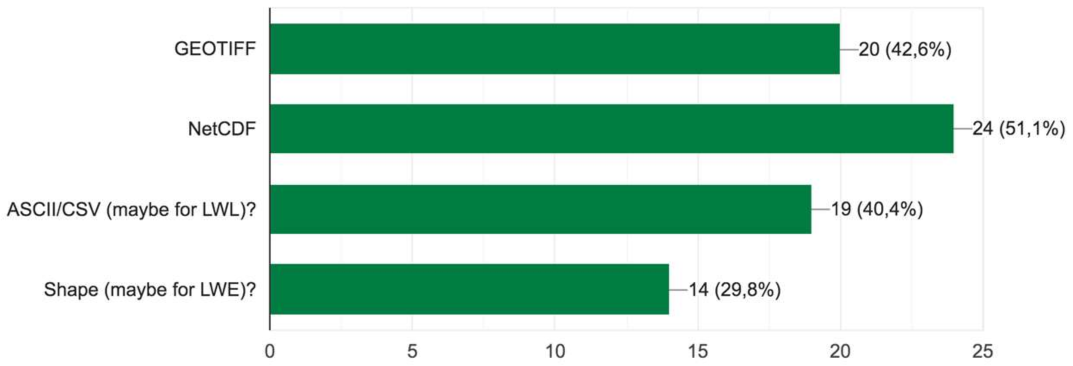


Figure 13. Histogram of answers to question 10

4.2.11. Requirements for uncertainty information

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).

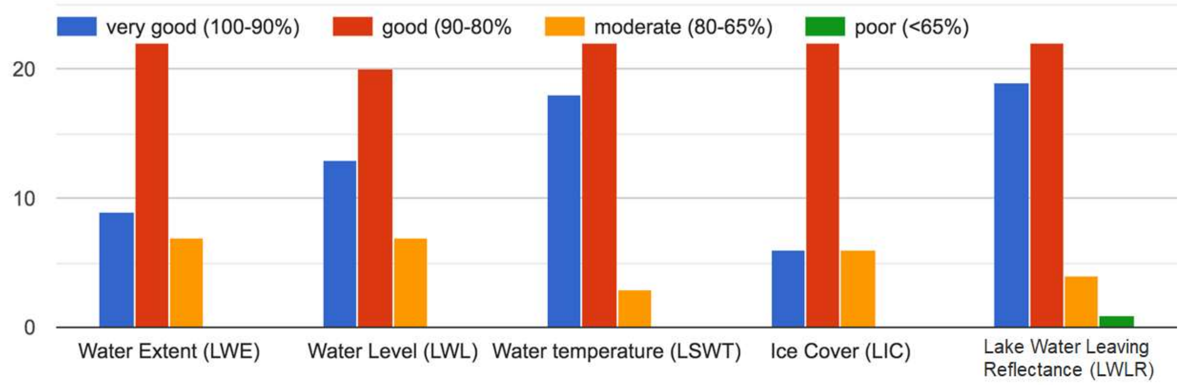


Figure 14. Histogram of answers to question 11

4.2.12. Requirements for projection

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).

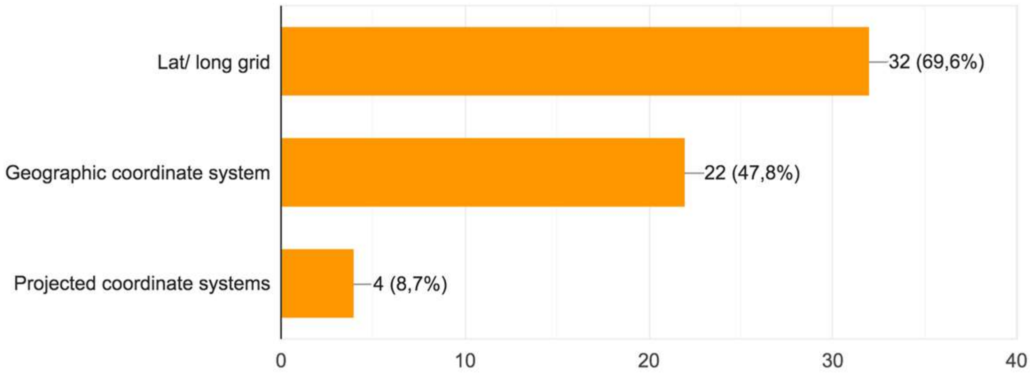


Figure 15. Histogram of answers to question 12

4.2.13. Requirements from free-form comments

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.

4.3. User consultations analysis

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. Between the lakes variables the major interest is addressed to lake water colour (LWLR), surface temperature (LSWT) and water level (LWL), while LIC and LWE are secondary required for the applications of the user communities interviewed.

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 important lakes 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.

4.4. Specific requirements from CRG

Within the consortium the CRG had the opportunity to answer both to the on-line survey as any other anonymous responder, and by specifying the lakes that would be included in the satellite data production. In Table 5 the list of lakes with most relevant parameters is outlined; for these lakes the longest possible time series would be required in order to perform the activities outlined in the by each use case.

The use cases are focusing 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 5. Details on lakes that have been indicated by the CRG for performing the activities for the four 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
Use case 3	Trasimeno	Italy	LSWT, LWR, LWL

Why	Name	Country	Parameters
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

4.5. Requirements from the literature review

A literature review was conducted to identify well-established methodologies and requirements for the science community, which study 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 6, 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 6. 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)

LAKE VARIABLE	ADVANTAGE/DISADVANTAGE	REFERENCES
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 feedbacks, **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.

4.5.1. Summary of requirements from the literature

Here is a list summarising the most relevant requirements that are implied by 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, of which all are to some extent addressed via the GCOS definition of the ECV (albeit that additional steps would be 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 -- which is to say everywhere
- Lake types of particular sensitivity must be observed: endorheic and thermokarst lakes
- Methods: from literature review, remote sensing has been considered a valuable tool for the studies referred to above on Lakes_cci parameters
- Data records need to be at least decadal and as long as possible

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 cycle (Table 7).

Table 7. 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 1km2 is an arbitrary value coming from the fact of the SAR measurements, are presumable accurately 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 mostly 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 requirement which is to estimate this value 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 km2) 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 it is more adapted to monitor LWL in order to identify 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 consider 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. Since the scientific requirement here is sensitive, such as 10% in the trend, which suggests 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 to radar 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 work has been achieved with satellite observations at 250-1000 m (e.g. MODIS, AVHRR) on medium to large size lakes, but to include smaller water bodies a 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, in which case a target spatial resolution of 30 m would be more appropriate. However, such resolution is currently not achievable at both the temporal resolution (daily) and length of historical record (ca. 20 years or more) needed 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 NASA's 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, albeit it with 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 a target for 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 so 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} at 1 mg chl-a m^{-3} or 1 g suspended matter m^{-3}, respectively.

The most stringent requirement on observational stability comes from comparing seasonal dynamics across decades. Both 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 8 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 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 given by superscripts on the targets as follows:

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

Table 8. 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)

Table 9 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 both given where relevant.

Table 9. 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, a user questionnaire and the experience of the project team. These are set out in section 6 as a first point of comparison for the future products of the Lake_cci.

So far, the analysis performed in this document is reflecting the needs of a broad community of users (from limnologists, to hydrologist, to climatologists) even if, being the project focused on climate change, the requirements from climate community will be primarily considered. For example, to this aim the Lake_cci user workshop is organised jointly to the 6th workshop on Parameterization of Lakes in Numerical Weather Prediction and Climate Modelling (Toulouse, France, October 22-24, 2019). The workshop will offer the opportunity to collect/revise the needs from an international well focused community on climate modelling.

Future developments of the understanding of user requirements will be developed through the project in the following ways:

- Survey users of Lake_cci products. Once Lakes_cci products have been available to users for ~1 year, we plan a further questionnaire, specific to the products, addressing ease of access and use, relevance of documentation, and experience with the product contents.
- Collation of requirements opportunistically. Implied and explicit requirements will be solicited and captured from questions and interviews at conferences, workshops, etc, attended by project team members;
- User case studies. We will analyse the experiences obtained from the user case studies based on first version of Lakes_cci CDRs for further requirements.

An update/revision to this User Requirement Document (version 2.0) in the light of the above will be prepared towards the end of this Lakes_cci phase.

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