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People involved in this issue:			Signature
Written by (*):	G. Free, C. Giardino, M. Pinardi, M. Bresciani	CNR	
	C. Merchant	UoR	
	A. Tyler E. Spyrakos	UoS	
	K. Stelzer J. Scholze	BC	
	A. Scrieciu	GeoEcoMar	
	A. Costantinescu	GeoEcoMar	
Checked by (*):	J. F. Crétaux	LEGOS	
	S. Simis	PML	
Approved by (*):	B. Coulon	CLS	Bruno Coulon Signature numérique de Bruno Coulon Date : 2021.12.06 18:38:29 +01'00'
Application authorized by (*):	Clement Albergel	ESA	

In the opposite box: Last and First name of the person + company

Distribution:		
Company	**Names**	**Contact Details**
ESA	C. Albergel	clementalbergel@esa.int
BC	K. Stelzer	kerstin.stelzer@brockmann-consult.de
CLS	B. Coulon B. Calmettes A. Mangilli P. Thibaut	bcoulon@groupcls.com bcalmettes@groupcls.com amangilli@groupcls.com pthibaut@groupcls.com
CNR	C. Giardino M. Pinardi	giardino.c@irea.cnr.it pinardi.m@irea.cnr.it
Eola	E. Zakharova	zavocado@gmail.com
GeoEcoMar	A. Scrieciu	albert.scrieciu@geoecomar.ro
H2OG	C. Duguay Y. WU	claude.duguay@h2ogeomatics.com mark.wu@h2ogeomatics.com
LEGOS	J.F. Crétaux A. Kouraev	jean-francois.cretaux@legos.obs-mip.fr alexei.kouraev@legos.obs-mip.fr
NORCE	E. Malnes	eirik.malnes@norceresearch.no
PML	S. G. H. Simis	stsi@pml.ac.uk
SERTIT	H. Yésou	herve.yesou@unsitra.fr
TRE-ALTAMIRA	P. Blanco	Pablo.blanco@tre-altamira.com
UoR	C. Merchant L. Carrea	c.j.merchant@reading.ac.uk l.carrea@reading.ac.uk
UoS	A. Tyler E. Spyrakos	a.n.tyler@stir.ac.uk evangelos.spyrakos@stir.ac.uk

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1. Executive summary

Lakes are of significant interest to 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. As well as being a vital resource for freshwater supply, lakes are key sentinels for global environmental change. Remote sensing can be an opportunity to extend and complement measurements at different scales of spatial-temporal analysis.

Within such a framework, Lakes have been selected as one of the Essential Climate Variables (ECVs) within the European Space Agency - Climate Change Initiative (ESA-CCI), a global monitoring program aiming to provide long-term satellite-based products to serve the climate modelling and climate user community.

In particular, the Lakes_cci project aims to produce and validate a consistent dataset of multiple thematic ECVs: lake water level, extent, surface temperature, surface reflectance, and ice cover. In April 2020 the first version of the Climate Research Data Package (CDRP) was produced and supplied on a mutually compatible spatio-temporal grid for 250 globally distributed waterbodies.

This document presents the second version of the Climate Assessment Report (CAR), which will be updated in 2022, to summarize the added value of Lakes_cci products and the activities of the Climate Research Group (CRG). Overall, the CAR first introduces the products generated by Lakes_cci. A second section on initial data exploration at global scale is also presented along with sample associated methodological steps. The specific activities from the CRG on five pre-defined use cases is then presented for addressing a variety of scientific questions. The CAR concludes confronting the progress made towards meeting user requirements and also includes main outcomes from the Lake_cci user workshop. This is followed by an updated list of publications, a summary of outreach activities and key conclusions.

2. Introduction

2.1. Purpose of document

This document summarises the current activities within the Lakes_cci in the context of the user requirements defined by the climate modelling user group (CMUG) and the wider community as further detailed in the user requirement document (URD v2.0). The principal objective of the Lakes_cci is to develop and enact methods to process and deliver the Climate Research Data Package (CRDP) for the Essential Climate Variables (ECV) Lakes as defined by the Global Climate Observing System (GCOS). The purpose of this CAR is to summarize the value of Lakes_cci products and related activities for climate science.

2.2. Structure of the document

The first part of the document introduces the products generated by Lakes_cci. The second part provides an assessment of these products leveraging learnings from five use cases currently being progressed by the consortium. A section dealing on initial data exploration at global scale is also presented along with the adopted associated methodological steps. The third part confronts the progress made towards meeting user requirements and also includes main outcomes from the Lake_cci user workshop. This is followed by an updated list of publications, a summary of outreach activities and key conclusions. This is the second CAR; it will be updated in 2022 to provide deeper analysis of an expanded CRDP and to reflect improvements and general product refinement during the project.

3. Introduction and rationale

The global increase in summer surface temperature has been estimated as 0.34°C decade^{-1} but the influence of local and lake specific parameters such as morphology means that responses can be complex (O'Reilly et al., 2015). Lakes are especially vulnerable to climate change. Variations in temperature and precipitation can profoundly affect the hydrological functioning of the lake and its catchment. Together with changes in ice formation, lake level and hydrogeochemistry the effect on lake ecological functioning can be significant (Adger et al., 2007; Cisneros et al., 2014). The thermal structure of the lake can be strengthened by an increase in temperature leading to deoxygenation and an alteration of nutrient cycling that in some cases exerts a stronger control than trophic status (Rogora et al., 2018).

Climate change is an important driver of global biodiversity in lakes and has been ranked third after invasive species and land-use change (Sala et al., 2000). Climate change will have a much more widespread and substantial effect in coming decades resulting from altered land cover, hydrology, nutrient cycling and species composition (Cardoso et al., 2009; Carpenter et al., 2011). Lakes often act as key reservoirs supplying water to the local human population and impacts can now include loss or restrictions to supply in temperate as well as arid and semi-arid regions. Water quality as well as quantity can be impacted with a deterioration through an increase in potentially toxic cyanobacteria with higher temperatures and more stable stratification in summer (O'Neil et al., 2012). The impact of reduced precipitation on lakes is likely to be augmented by increased pressure for abstraction for domestic and agricultural use directly from the lake and its upstream waters.

In addition, the disruption to climatic patterns can also result in more frequent storms with associated flooding (Cisneros et al., 2014).

In a recent review Woolway et al. (2020) summarized the responses of key physical lake variables and processes to global climate change, including ice cover, surface water temperature, evaporation, water levels and mixing regimes, and outlined their ecological consequences. In the same review Woolway et al. (2020) outlined how future efforts investigating lake responses to climate change need to be grounded in sustainable, systematic, multivariate observations for a consistent set of lakes. One effort in this direction is the ongoing European Space Agency Climate Change Initiative for Lakes (CCI Lakes), which coordinates a range of remote sensing techniques to address the lake ECVs identified by the GCOS. 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 of efforts such as CCI Lakes is that they focus on maximizing the benefit of legacy Earth observations made over the past decades, as well as developing better observational capabilities from current and prospective missions. State-of-the-art observational data sets currently provide measurement time series of lake state for a few hundred lakes. Based on current and historic sensors, records of combined temperature, reflectance and optically derived lake ice state observations for roughly 10,000 lakes may prove tractable with improved remote sensing methods.

Remote sensing has been identified as a key means by which to manage lakes – providing confidence and standardising approaches to assessment. More than ever, remediation or mitigation efforts are also required to deliver multiple co-benefits such as reducing flood risk as well as nutrient load (Carvalho et al., 2019). This project and its future iterations provide a framework to deliver such multiple benefits (i. e. lake water level and Chl-a products) in addition to complementing other essential climate variables already available. Some other recently identified key research gaps for lakes that the project is likely to aid include the means to extrapolate and assess ecological status in unmonitored lakes, provide information to aid hydromorphological assessment of the impacts of higher or lower lake levels as well as providing a fundamental component required to analyse the links between global change and ecosystem functioning (Reyjol et al., 2014; Free et al., 2020).

Lakes are also a unique and useful medium through which to gain perspective of the effects of climate change. Their nature as a semi-contained system – catchment and lake basin with distinct and fast moving seasonal succession of flora and fauna, especially in the plankton, marks them as rapidly responding ecosystems ideally suited to observe change. While the response may be complex resulting from interacting pressures, lake typology and position on the trophic gradient, there is also significant value in interpreting an integrated signal to understand the impact in the natural environment (Weyhenmeyer et al., 1999; Adrian et al., 2009).

Despite the benefits and clear strategic value, there is currently no consistent matched timeseries available at global level. Lakes_cci therefore aims to deliver spatially and temporally contiguous satellite derived datasets. The ESA driven initiative to augment ECVs in this area will enable multiple benefits and insights into lakes response to climate change as well as filling a key gap that will allow a more integrated global picture of the changes and response to climate change.

The following sections provide an initial assessment of some applications of the dataset to demonstrate its potential through selected case studies. Feedback on data use will be added in the next version of the CAR following the completion of the use cases and collation of experiences from other data users.

4. Products generated by Lakes_cci

Lakes_cci is developing the latest generation Earth Observation products for an initial set of 250 lakes distributed globally. The data set covers the full suite of thematic ECVs from 2002 to 2019, with some of these variables extending further back to 1992 with some gaps depending on satellite sensor availability. Given the diversity of variables measured, the methods used to collect, analyse and provide the data differ (see Product User Guide - PUG, Algorithm Theoretical Basis Document –ATBD - and product specification document - PSD). In addition, each variable has associated uncertainty estimates, gathered using a standard approach. While the processes of product optimisation are necessarily variable specific, the output is a consistent data format harmonised and supplied in the same temporal and spatial framework in NetCDF format.

The Lakes ECV dataset is composed of the following thematic variables:

- Lake Water Level (LWL)

Lake Water Level is the measure of the absolute height of the reflecting water surface beneath the satellite with respect to a vertical datum (geoid) and expressed in metres. LWL is a fundamental proxy to understand the balance between water inputs and water loss and their connection with regional and global climate changes.

- Lake Water Extent (LWE)

Lake Water Extent refers to the extent (or area) of a lake covered by water, it is a proxy for change in glacial regions (lake expansion) and drought in many arid environments. Water extent can influence the local climate, for example having a cooling effect. It also provides information relevant to processes in the littoral zone, a key habitat for many ecological groups such as macrophytes, macroinvertebrates and fish.

- Lake Surface Water Temperature (LSWT)

The Lake Surface Water Temperature LSWT is defined as the temperature of the water at the surface of the water body (surface skin temperature). LSWT is correlated with regional air temperatures and can be a proxy for mixing regimes, driving biogeochemical cycling and seasonality.

- Lake Ice Cover (LIC)

Lake ice cover (LIC) refers to the extent (or area) of a lake covered by ice; freeze-up in autumn and advancing break-up in spring are proxies for gradually changing climate patterns and seasonality.

- Lake Water Leaving Reflectance (LWLR)
    - Chlorophyll-a
    - Turbidity

Lake Water-Leaving Reflectance (LWLR), also referred to as water colour, is the measurement of the quantity of sunlight reaching the remote detector after interaction with the water column. From LWLR, chlorophyll-a (Chl-a) and Turbidity have been derived. LWLR hence provides direct indicators of biogeochemical processes in the visible part of the water column (e. g. seasonal phytoplankton biomass fluctuations), and the frequency of extreme events (e. g. peak terrestrial run-off, changing mixing conditions).

5. Assessment of products

The data presented in this report is based on the first version (1.1) of merged satellite products (Crétaux et al., 2020), which have the following main characteristics:

- Spatial coverage: 250 globally distributed lakes
- Spatial resolution: 1/120 degrees grid
- Temporal resolution: daily
- 1 netCDF file per day containing all thematic variables
- Temporal coverage: From 1992 up to 2019 (shorter ranges for some variables as follows, figure 1):

Figure 1. Temporal coverage of the five thematic ECVs

5.1. The CDRP at a glance

5.1.1. Distribution of Lakes_cci

The 250 target lakes from the first version of the dataset are distributed globally (red in figure 2). Future updates will include more lakes, filling gaps globally where possible (e.g. New Zealand). It is planned that close to a total of 2000 lakes will be available in late 2021 when CDRP2 is delivered (blue in figure 2).

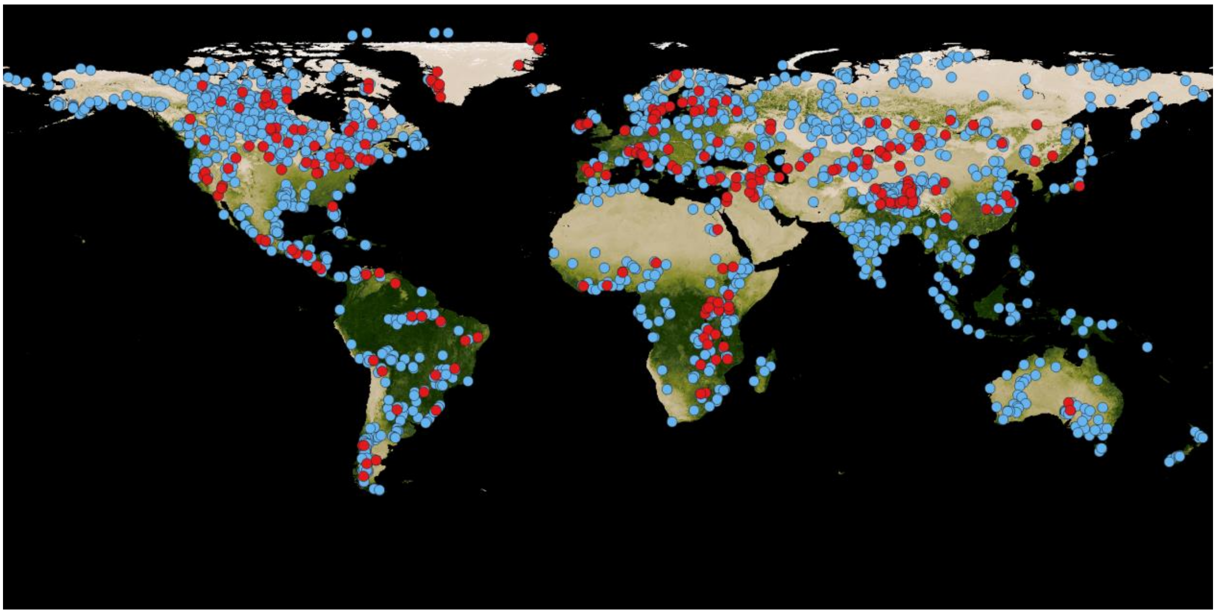

Figure 2. Global distribution of the CCI lakes (Red = CDRP V1.1, Blue = CDRP V2 additional lakes).

5.1.2. Initial data exploration

In order to provide an initial indication of the distribution of values of the ECVs at global level, data were extracted from the NetCDF files in the CDRP. Uncertainty layers associated with the ECVs were used to filter the data. The level of acceptable uncertainty is, of course, application-specific. For example, if chlorophyll-a was used for status assessment under the European Water Framework Directive (WFD) a selection of uncertainty values could be tested to see if they give adequate confidence in assessment. Figure 3 shows confidence curves for 50 and 60% uncertainty but indicates that there is little difference in confidence assigned to a classification derived from chlorophyll-a using either level. This 'uncertainty in the uncertainties' ultimately derives from limited availability of in situ reference observations (see E3UB). Approaches to the use of uncertainty layers and further data selection performed for this example are listed in Table 1. Data processing used the linear interpolation TSGFlinear function of the r package 'greenbrown' that carried out a linear interpolation with smoothing using a median window size of three (Forkel & Wutzler, 2015). This gap filling assists in providing a more continuous dataset in order to give a preliminary general overview of the data distribution, whereas for case specific approaches tailored approaches together with validation should be employed. The following data processing steps were performed:

- Date formatting
- Filtering data according to associated uncertainty / quality indicators (Table 1)
- Extraction of means based on shapefiles
- Removing the most extreme outliers (>15 times the inter-quartile range [IQR])
- Conversion to time series
- Filling gaps (using R package 'greenbrown')
- Deleting predictions where gaps were long (>30 days)
- Calculating monthly averages, then annual average.
- Some variables were normalised for comparison.

Table 1. Quality level filters used for extracting data. An example approach only – users should change specifications to meet their own requirements.

ECV	Applied approach
Temperature	Selection limited to lswt_quality_level 4-5
Ice cover	Count of pixels classified as ice (value 2 in the CRDP) - uncertainty is a standard value.
Level	Judgement based – filtered by ≤0.1 m uncertainty.
Extent	Only 12 lakes – error is standard value per lake – not filtered.
Chlorophyll-a	90% of fractional uncertainty ranged between 39-60% - therefore the choice is not crucial as selection within this range will not have a large difference on confidence in trophic classification (Fig. 1). A selection of 60% was used.
Turbidity	90% of fractional uncertainty ranged between 59-80% - similar to chlorophyll-a an uncertainty of 70% was chosen.

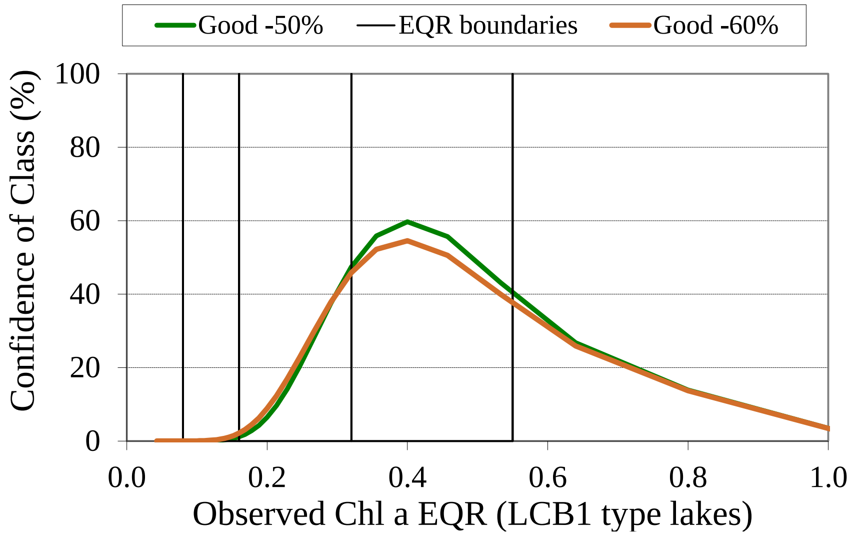

Figure 3. Confidence of class curves for the good ecological class under the European WFD for lake type LCB1 (Central Baltic geographic intercalibration group). The five classes are indicated by vertical lines descending from High, Good, Moderate, Poor and Bad. Confidence in the good class does not change much selecting between 50 or 60% uncertainty.

An example of the distribution of chlorophyll-a, calculated as an annual average for each lake, for the global dataset between 2002 and 2019 is shown in figure 4. Most of the concentrations are centred around 10 mg m^3 chlorophyll-a with no large change in the global dataset over time. Similarly, there were no clear discernible differences in the spatial variation of concentrations, perhaps with the exception of the higher concentrations in Europe and North America (figure 5). It is likely that concentrations and trends vary depending on localised activities in the catchment with potential modification by climate change, a theme that will be explored in several case studies.

Plots for the other ECVs to indicate the data distribution over time, calculated per lake, are shown in figure 6 to figure 10. The representation of the distributions are preliminary and are intended to provide an initial broad overview of the dataset. Of note is the bimodal distribution of temperature owing to the distribution of the lakes in either temperate regions or closer to the equator (figure 7); more detailed global definition of thermal lake types has recently proven a useful approach for anticipating shifts using climate projections (Maberly et al., 2020). In addition, some lakes have shown significant deviation in lake extent, increasing or decreasing by a quarter (figure 9). Most of the other distributions are reasonably stable over time, but, as with chlorophyll-a, increases in some lakes could be balanced by decreases in others, necessitating specific examination as being carried out in the case studies.

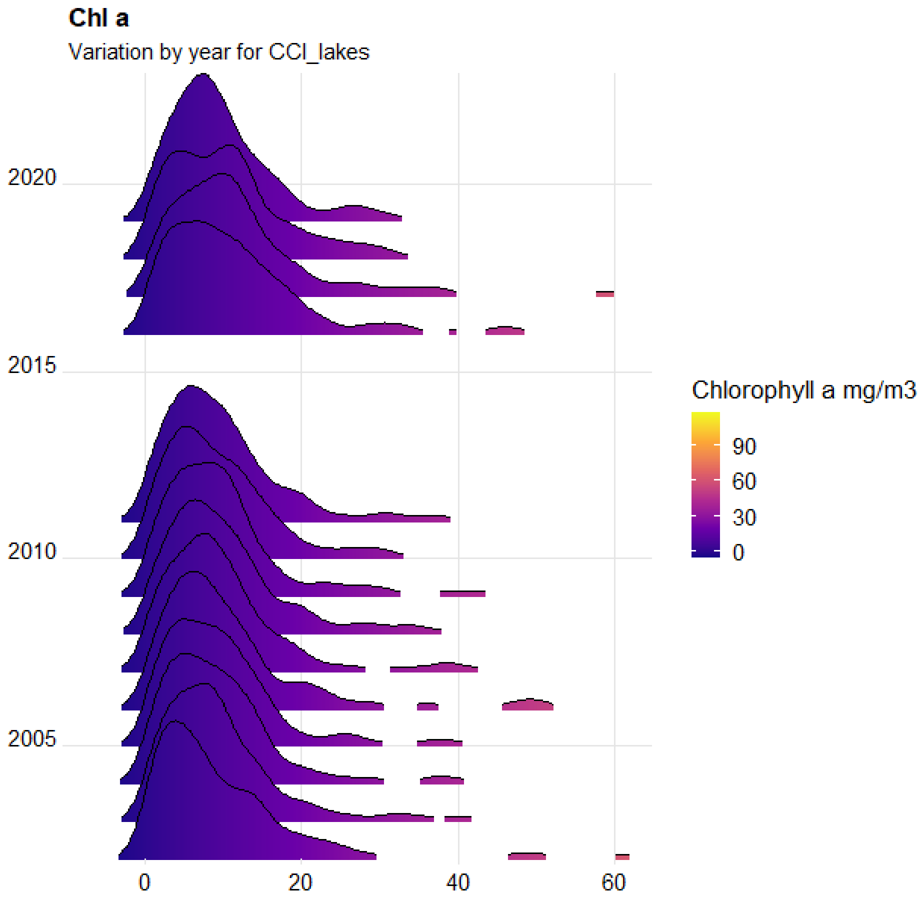

Figure 4. Distribution of chlorophyll-a concentration, annual average calculated per lake, for the global dataset from 2002 to 2019. Some high values of chlorophyll-a removed for clarity. Data from CDRP V1.1.

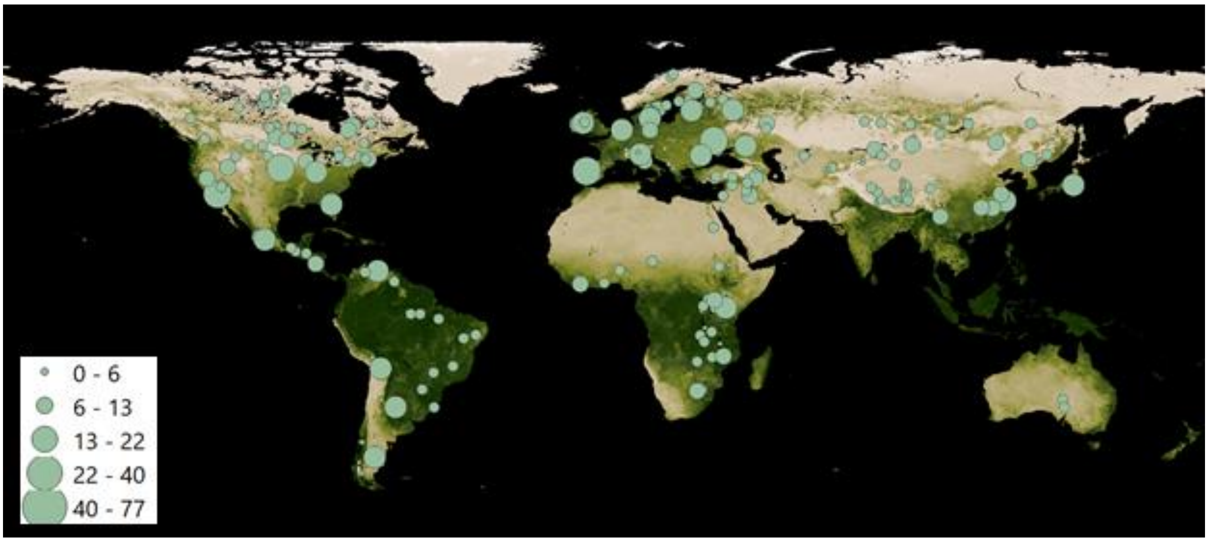

Figure 5. Distribution of average chlorophyll-a concentration (mg/m^3) for the global dataset from 2016 to 2018. Data from CDRP V1.1.

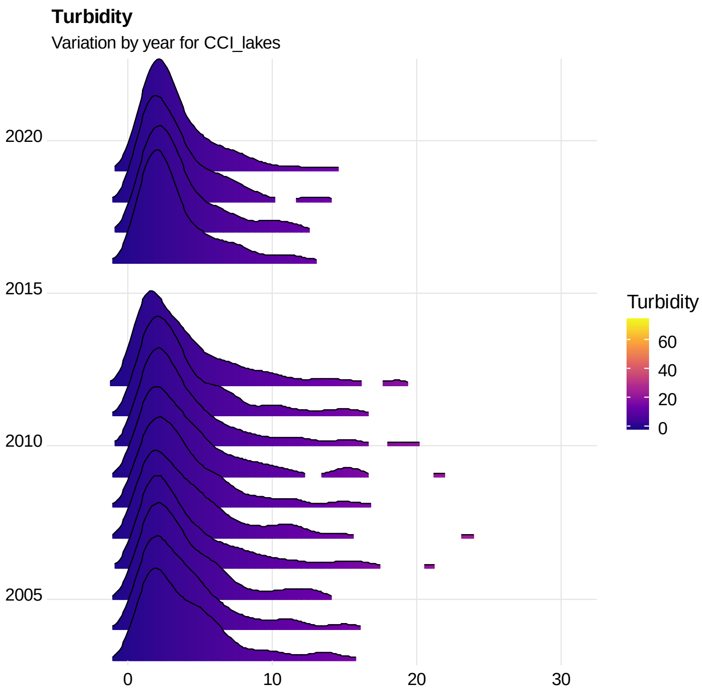

Figure 6 Distribution of turbidity (NTU), annual average calculated per lake, for the global dataset from 2003 to 2019. Some high values were removed for clarity. Data from CDRP V1.1.

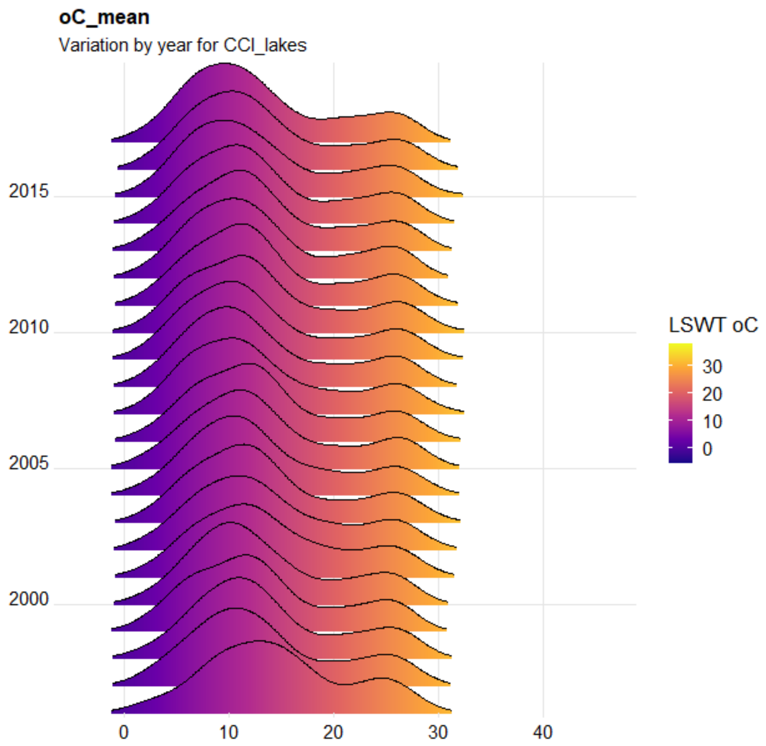

Figure 7. Distribution of lake surface water temperature ºC (LSWT), annual average calculated per lake, for the global dataset. Note bimodal distribution derived from lakes being either closer to temperate or equatorial regions. Data from CDRP V1.1.

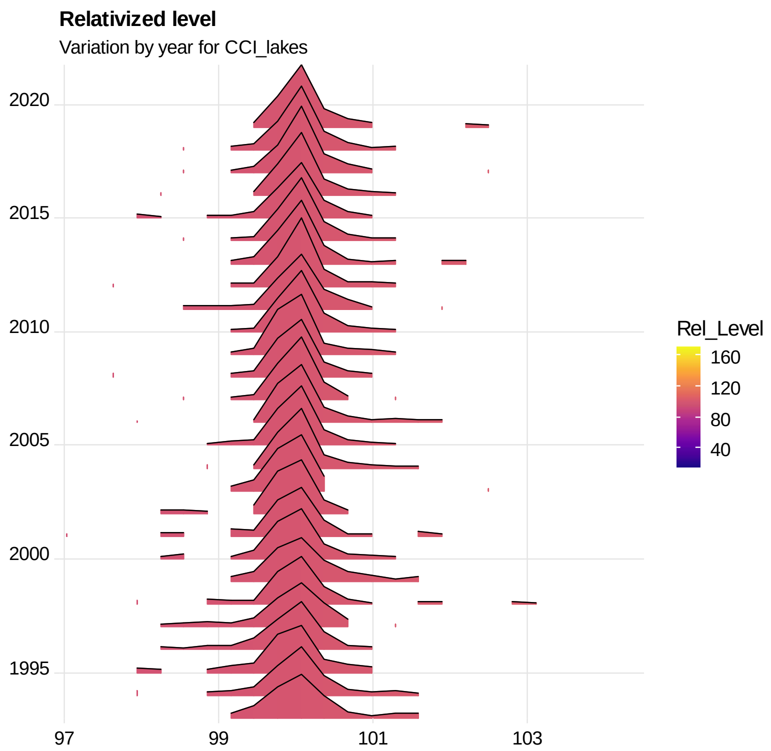

Figure 8 Distribution of normalised (%) lake level, calculated per lake as annual average divided by time-series average, for the global dataset. Scaled between 97-103% for clarity. Data from CDRP V1.1.

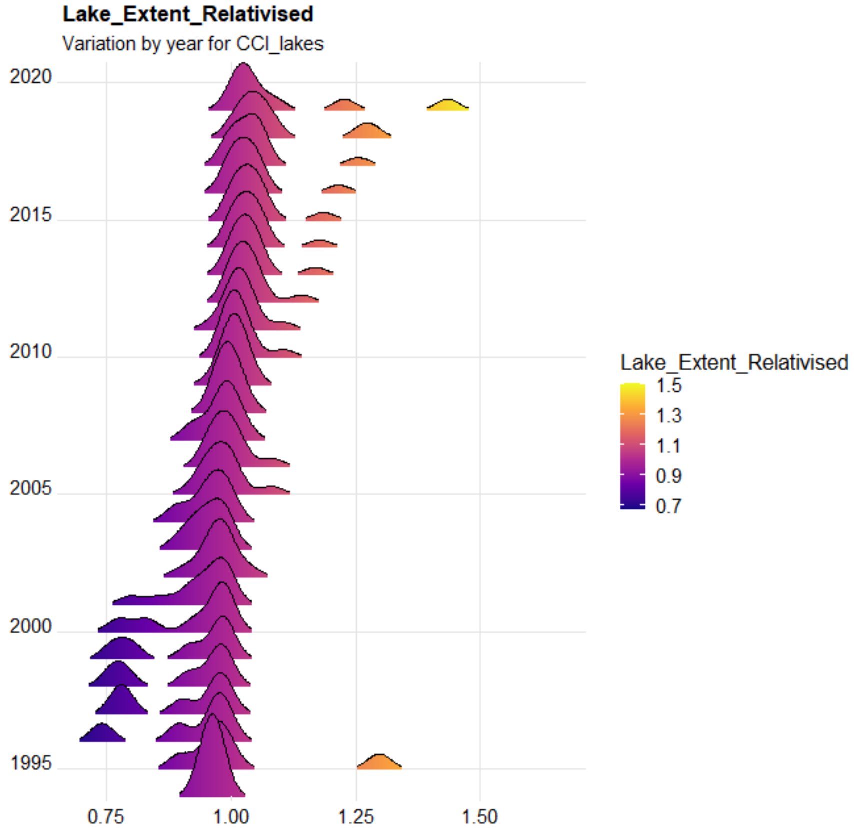

Figure 9. Distribution of normalised lake extent, calculated per lake as annual average divided by time-series average. Data from CDRP V1.1.

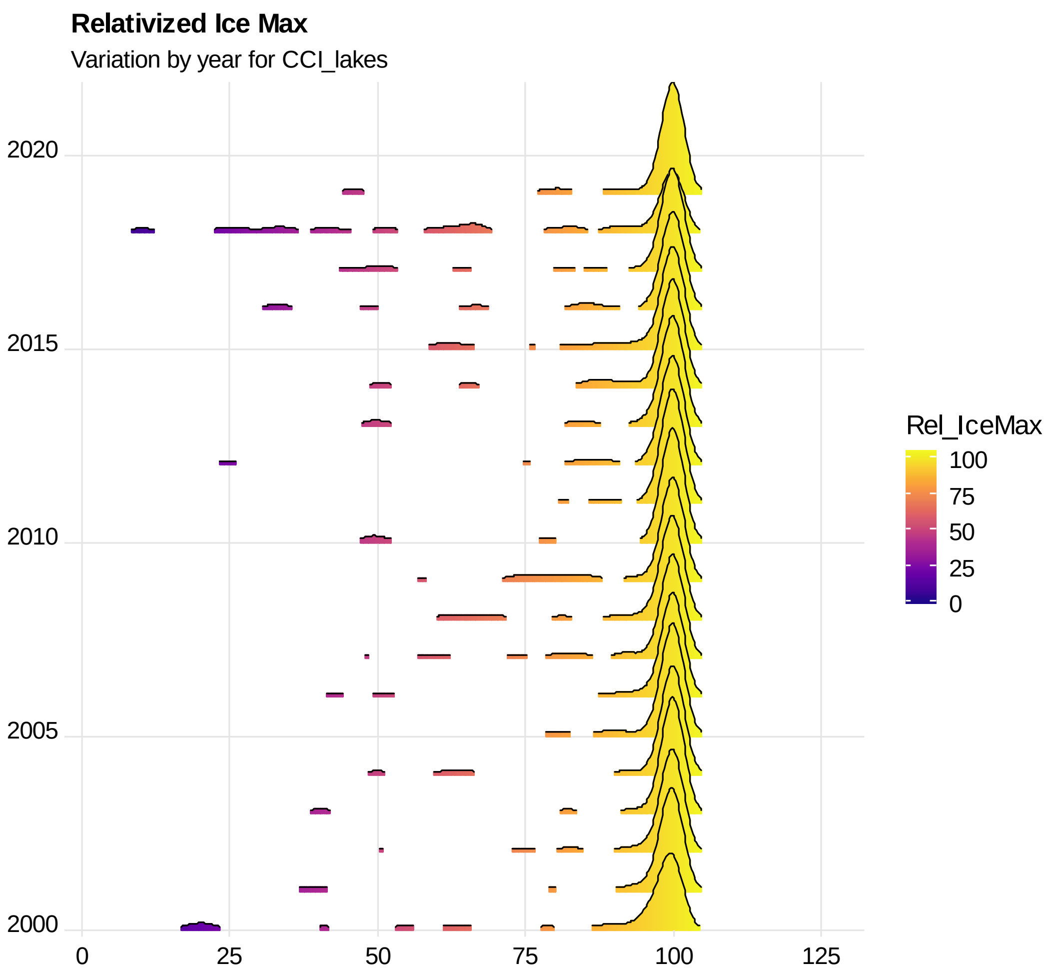

Figure 10. Distribution of maximum annual ice extent (%), calculated per lake as annual maximum divided by time-series maximum, for the global dataset. Data from CDRP V1.1.

5.1.3. Potential links and analysis with other climatic datasets

With the expanding suite of essential climate variables (https://gcos.wmo.int/en/essential-climate-variables/) and continually refined global climate reanalysis data https://climate.copernicus.eu/climate-reanalysis) - already extended back to 1950, there exist opportunities to explore linkages with a wide variety of climatic datasets. For example, potential linkages between the lake ECV for ice cover and the ECVs for glaciers could be explored. There are many other ECV connections worth exploring owing to the close interconnectivity between lakes and their catchments and their dependence on regional climate and water cycles. Other obvious relevant ECVs include river discharge, groundwater, terrestrial biosphere ECVs for the relevant catchments, as well as anthropogenic water use. In addition, the global climate reanalysis data provides more opportunities - for example utilizing some of the key ERA5 variables, listed below, in conjunction with the FLAKE model to understand lake mixing regimes (see Woolway et al. 2019).

- 10m u-component of wind
- 10m v-component of wind

- Total precipitation
- 2m temperature (example of trend analysis in following slides)
- Surface solar radiation downward
- Surface thermal radiation downward
- Specific humidity
- Fraction of cloud cover

Accessing the ERA5 database we can extract air temperature data (2m) from 1980-2019 for the Lakes_cci data set (https://climate.copernicus.eu/climate-reanalysis). It can be seen that the vast majority of the lakes had positive slopes and that most of these were significant (Figure 11, Figure 12).

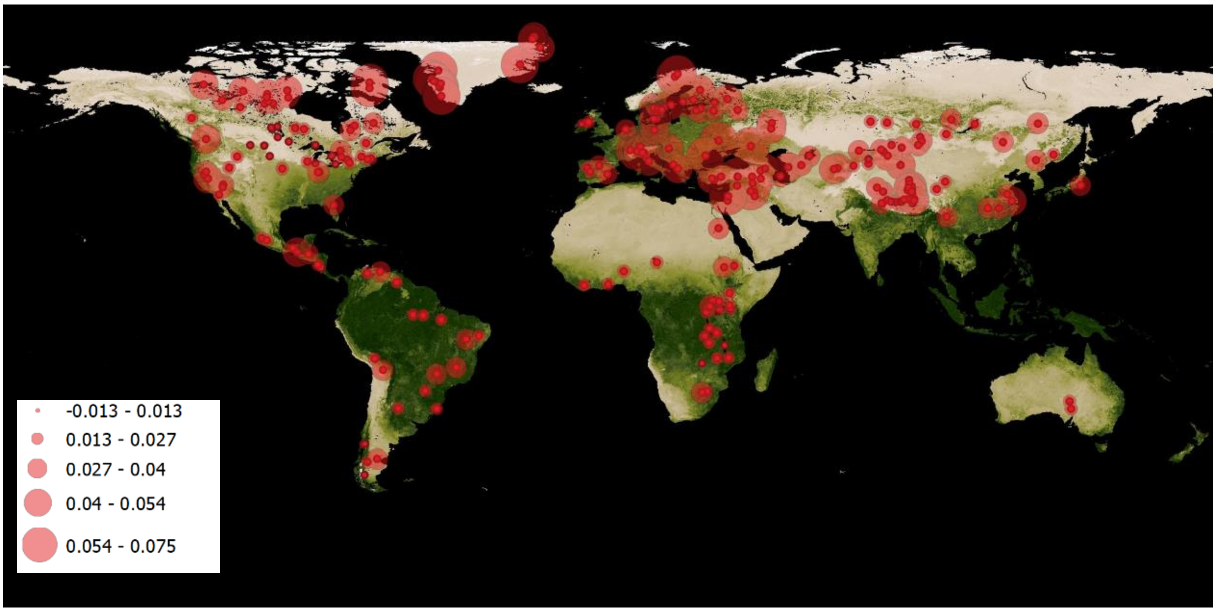

Figure 11. Slope of air temperature increase for 1980-2019 for the lakes targeted by Lakes_cci. Data from ERA5.

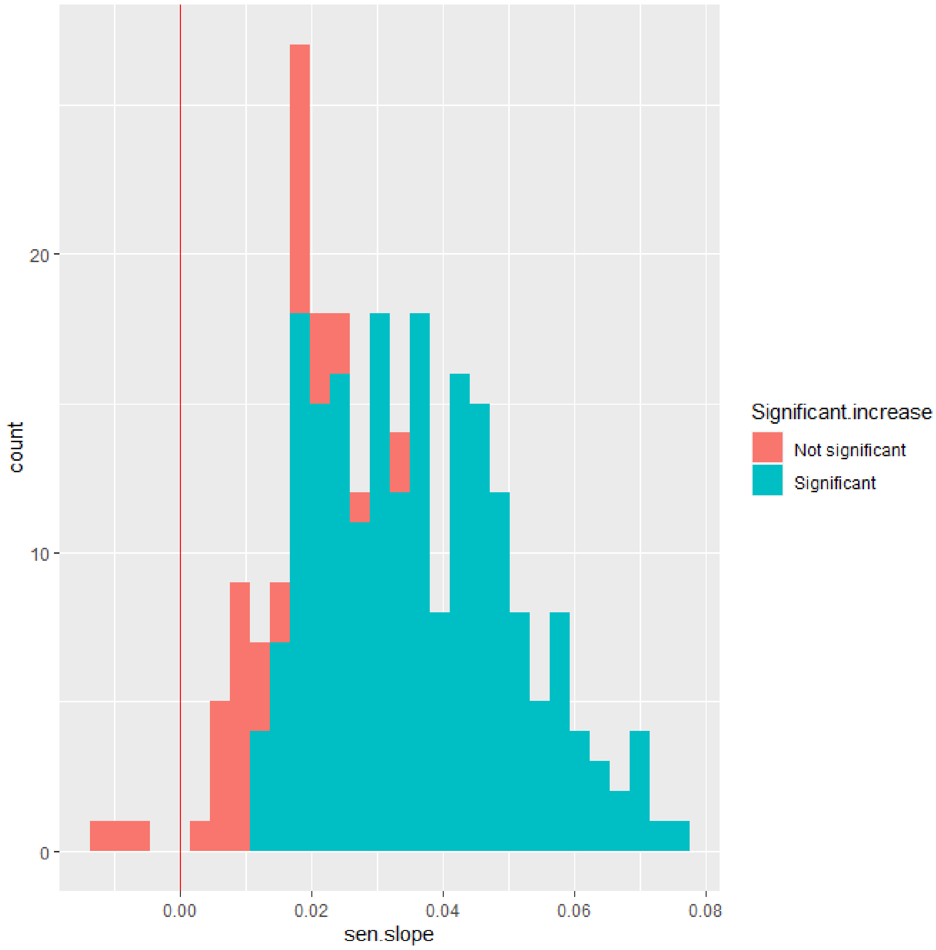

Figure 12. Stacked histogram of Sen slope for test of trend in air temperature from 1980-2019. Vast majority of slopes are positive and significant (blue). Red line = slope of 0. Data from ERA5.

5.2. Use cases

5.2.1. Science Use case 1 Greenland lakes

This use case focuses on joint analysis of lake surface water temperature (LSWT), lake ice cover (LIC), lake water level (LWL) and Glacier CCI (GLA) ECVs for lakes in Greenland. Climatic modification of LSWT, LIC and LWL has important implications for ecosystems and Greenland is considered to be highly susceptible to global warming (Hanna et al., 2008). The Greenland ice sheet has undergone accelerated warming and could result in significantly weakened Atlantic Meridional Overturning Circulation by the end of the century (Bakker et al., 2016). A detailed understanding of how the ECVs vary in response to climate change, and the factors controlling their variability, is therefore essential for climate change impact studies.

This use case investigates the temporal dynamics and covariation of LSWT, LIC, and LWL linking relevant GLA data and surface air temperature (SAT) obtained from climate re-analysis and weather stations. The links between SAT-LSWT-LIC-GLA and other factors are complex. LSWT changes reflect in some cases changes in glacial run-off and in forcing by air temperature. Some lakes in the region warm faster than SAT, while others (driven by increased glacial water flows) cool. LWL is useful in this regard providing an integrated mass balance from changes in inputs (precipitation and runoff) compared to evaporation.

Factor analysis will be applied to help predict how these lakes will respond under future climate change. There is a current debate in the scientific community studying lake responses to climate change over the relative roles of enhanced glacier and permafrost thawing and other climatic drivers. The lack of in situ data also strengthen the need to exploit remote sensing information on the different ECVs over a set of lakes in Greenland. Despite the rapid rate of change in the region the current lack of monitoring has been identified as an impossible barrier to the prediction of ecosystem service change in this environment (Heino et al., 2020). A key output therefore will be to provide background standardised information on environmental change upon which the scientific community can build. In the initial phase of the analysis, significant data gaps in the LSWT data were identified with lower than 20 records for some years, particularly for the ATSRs era (until 2007). Therefore, processes were instigated to retrieve LSWT from the MODIS sensor on the Terra satellite with data available from the year 2000 onwards. LSWTs from SLSTR sensors onboard Sentinel3A and Sentinel3B will be also included from 2016 onwards. This should allow for a more robust analysis of the thermal behaviour over time with improved uncertainties. The study will focus on quantifying changes over time in metrics including annual cycles, maximum temperatures and stratification timing.

5.2.2. Science Use case 2 Analysis and interpretation of ECVs for large lakes

Use case 2 focuses on analysis and interpretation of lake water leaving reflectance (LWLR) and Lake Surface Water Temperature (LSWT) for large lakes (>500 km^2) in Europe, Africa, Central and South Asia and Central and South America. The aim is to determine the temporal and spatial dynamics of lake surface reflectance in relation to temperature change and a climatic gradient.

Using ground data, the capabilities of both in situ and satellite-based data to detect climate change signals is being contrasted at both temporal and spatial scales. Using the lakes_CCI products two fundamental questions are addressed:

- Is change in lake water-leaving reflectance (Chl a, CDOM or Rrs) driven primarily by temperature?
- Is there a significant pattern (geographical or otherwise including phenology) in the coherence between the lake water-leaving reflectance and LSWT ECVs?

Time series and statistical analysis is used to ensure consistency and validity of ECVs and result in the identification of key drivers of ECV change. The hypothesis of this use case is that patterns in water quality will be coherent with and attributable to trends in LSWT. Generally speaking, we expect that direct anthropogenic exploitation and management of lakes may partially mask the physical-biological response. However, in very large lakes this response is more likely to remain directly observable. Our expectation is that this will depend on how the ECVs are interpreted, for example magnitude of response vs delayed response to the LSWT driver (Kraemer et al., 2015; O'Reilly et al., 2015). The gradients of the observed changes in magnitude and phenology of events will be explored according to proximity with other climatic drivers. Where the response is not consistent with the hypothesis, efforts will be made to explore what the likely drivers of change may be.

The key output will be a framework to assess the resilience of lakes to changes in temperature and climate and highlight where differences to the expected response occur, possibly resulting from related or independent drivers of environmental change such as nutrient input, insolation (relating to cloud cover and water vapour ECVs, and water flushing rate). This can inform response planning at global (UN) or regional level (e. g. EU) guiding the incorporation of EO into strategies to achieve sustainable development goals.

Initial work filtered data for quality levels, excluded data based soley on unrepresentative parts of the lake and excluded months that had significant ice cover. Data were then detrended using generalized additive model (GAM) to exclude annual trends to allow a focus on seasonal patterns of chlorophyll-a and turbidity to examine how they vary with temperature. Relationships were divided into either positive or negative with temperature and further classified as having a synchronous relationship with temperature or a pattern that either preceded or succeeded that of temperature. Initial results showed that 59% of the lakes have a negative relationship between chlorophyll-a and temperature (figure 13), 64% of the lakes have a positive relationship between turbidity and temperature (figure 14). Analysis is currently ongoing and revealing differences between lakes in different lake thermal regions, and change of patterns in the past twenty years.

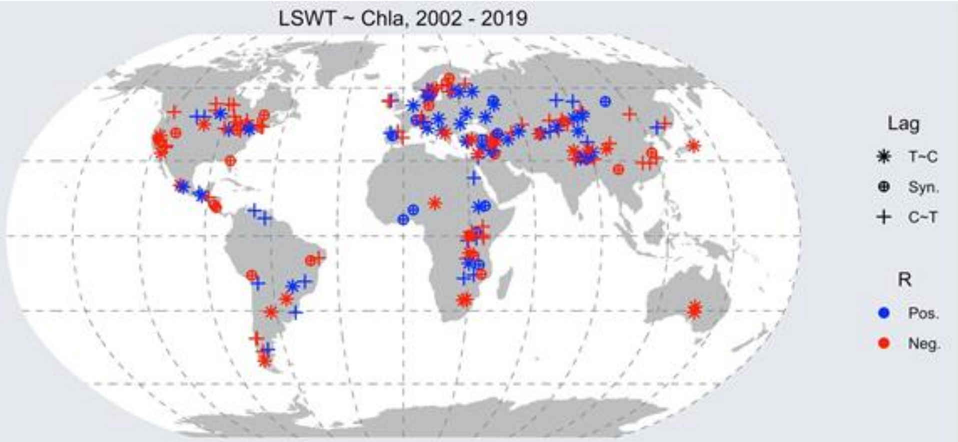

Figure 13: Relationships between time series lake surface water temperature and chlorophyll-a. Blue represents positive relationships, red represents negative relationships. Asterisk represents chlorophyll-a follow temperature changes, sun cross represents chlorophyll-a and temperature have synchronous changes, cross represents temperature follow chlorophyll-a changes. Data from CDRP V1.1

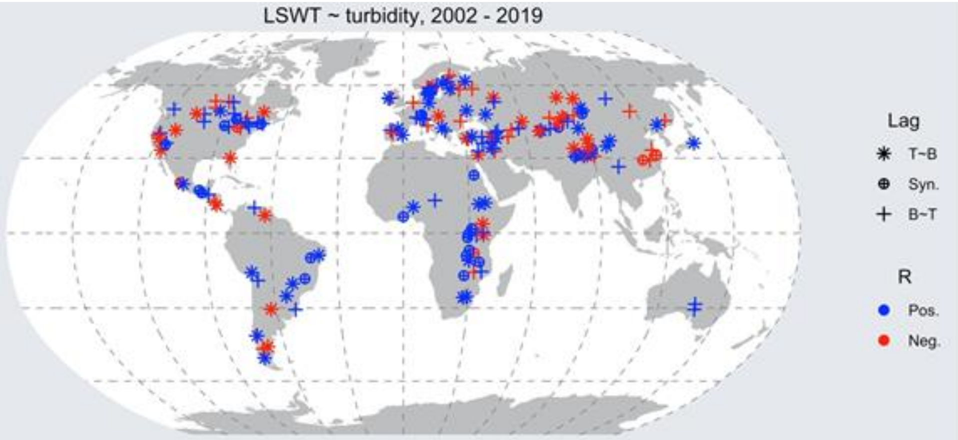

Figure 14: Relationships between time series lake surface water temperature and turbidity. Blue represents positive relationships, red represents negative relationships. Asterisk represents turbidity follow temperature changes, sun cross represents turbidity and temperature have synchronous changes, cross represents temperature follow turbidity changes. Data from CDRP V1.1.

5.2.3. Science Use case 3 Exploiting ECVs in Long Term Ecosystem Research

The use case 3 has a particular focus on the Long-Term Ecosystem Research (LTER) network that concentrates on studies of ecological processes that operate at diverse temporal and spatial scales. The LTER sites are distributed across the globe and at different latitudes. These sites include European lakes (e. g. Garda, Maggiore, Trasimeno, Balaton and Erken), north temperate lakes in North America (e. g. Mendota) and lake Taihu in China. These lakes have unique and distinct features that, in response to climate change might vary significantly (e. g. Magee and Wu, 2017; Palmer et al., 2015; Salmaso 2005; Ludovisi et al., 2005; Morabito et al., 2003; Blenckner et al. 2002).

Within this use case, the ECVs are combined with LTER data to perform an assessment of vulnerability in predefined lakes with regard to climate change and other environmental stressors. The Lakes_cci variables that are of primary importance are LWL, LSWT, LWLR (and derived turbidity and chlorophyll-a concentration). The use case also aims to assess future impacts from climate change scenarios on the lake (e. g. water quantity, quality and temperature). This evaluation will be particularly relevant for the public and stakeholders of the different, often conflicting, interests related to the water use.

This use case aims to demonstrate that the Lakes_cci variables add significant value to the interpretation of what are often complex drivers of change and will aid the development of sustainable water management strategies in LTER sites. For example, urban sprawl, air and water pollution, and habitat fragmentation are already stressing the lakes ecosystems of Mendota and Garda, while global climate change looms as an additional threat on the region's economy, population and wildlife by changing climate patterns and compounding the negative effects of current environmental problems.

In particular, the availability of spatial and temporal trends of Lakes ECVs is relevant to assess the inter-annual variations of the trophic status in oligomictic and meromictic parts/seasons of temperate lakes depending on the climatic evolution during the coldest months and the water-mixing dynamics. For southern latitudes, this study would further explore the alterations of the thermal and hydrological balance of lakes which has already caused a progressive decrease of water level. By projecting observed trends into the future scenario of climate change, an accelerating drought and progressive worsening of the water quality might be predicted for shallow water lakes (e. g. Trasimeno) in the near (mid-century) and less certain (end-century) future.

The first phase of work from this use case focused on four large deep sub-alpine lakes in Italy. A significant change in the seasonal pattern of chlorophyll-a occurred between 2003-2018 (Figure 15). There was a shift from a dominant spring peak, clear water phase and summer peak to a weakened spring peak with more prominent summer concentrations. This shift was interspersed by a period of low chlorophyll-a. The key driver is likely to be the higher winter temperatures linked to the failure since 2005/2006 of the lakes to fully mix resulting in lower nutrient concentrations in the epilimnion. The satellite estimation of chlorophyll-a and its capacity to gather a synoptic regional picture may have proved essential in revealing the changing trend over this 16 year period (Free *et al.*, 2021).

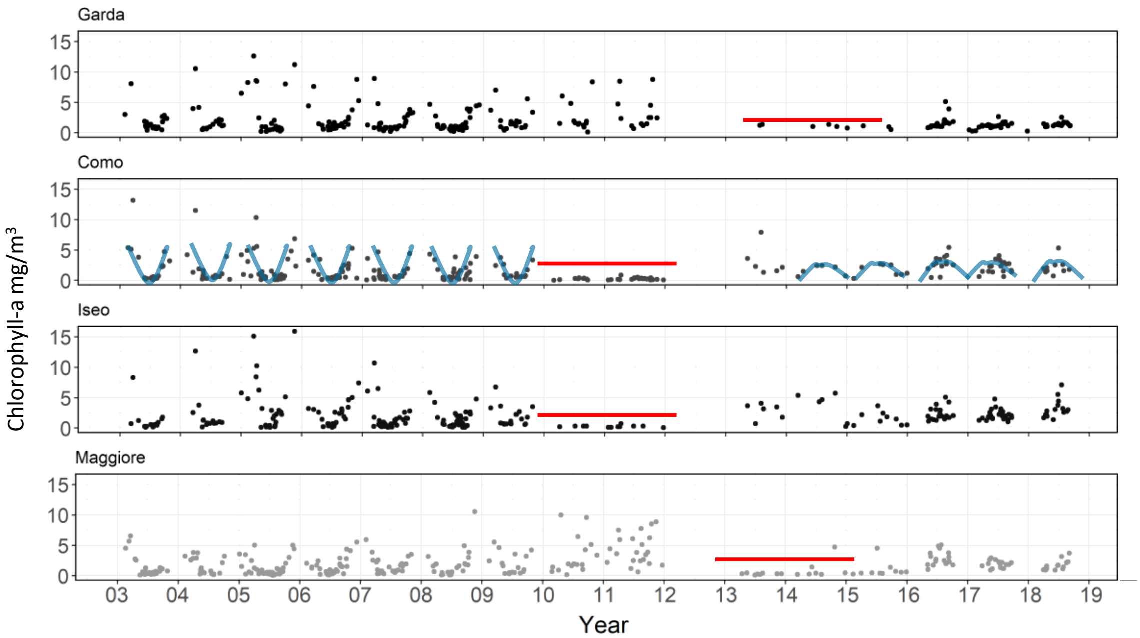

Figure 15Chlorophyll-a derived from satellite in four subalpine lakes from 2003-2018. Periods of low chlorophyll-a are indicated by a red line and the change in pattern from a concave to convex seasonal pattern are highlighted for Lake Como with a blue line.

The CCI lakes dataset was used to examine the phytoplankton bloom dynamics for shallow eutrophic lake Trasimeno. It had a well-defined summer bloom and its seasonal timing could be described using satellite data dating back to 2003. Larger summer blooms were associated with higher total phosphorus concentration (**Erreur ! Source du renvoi introuvable.**), warmer temperatures, a lower lake level and a more positive NAO, indicative of high pressure and warm sunny calm weather. The relative role of these parameters and other factors in influencing Chl-a was difficult to apportion because they are correlated seasonally. Interestingly, blooms were not occurring earlier but the length of season where water temperatures were above 20 °C appeared to play a role in controlling the duration of blooms. A longer warmer season, typically commencing earlier in the year was found to lead to a shorter duration of blooms likely owing to seasonal nutrient limitation and perhaps increased calcite precipitation. As the duration of warmer temperatures is increasing this is likely to be more important in the future with implications for species phenology and lake ecosystem functioning (Free *et al*. 2021 under review, Bresciani *et al*., 2021 accepted).

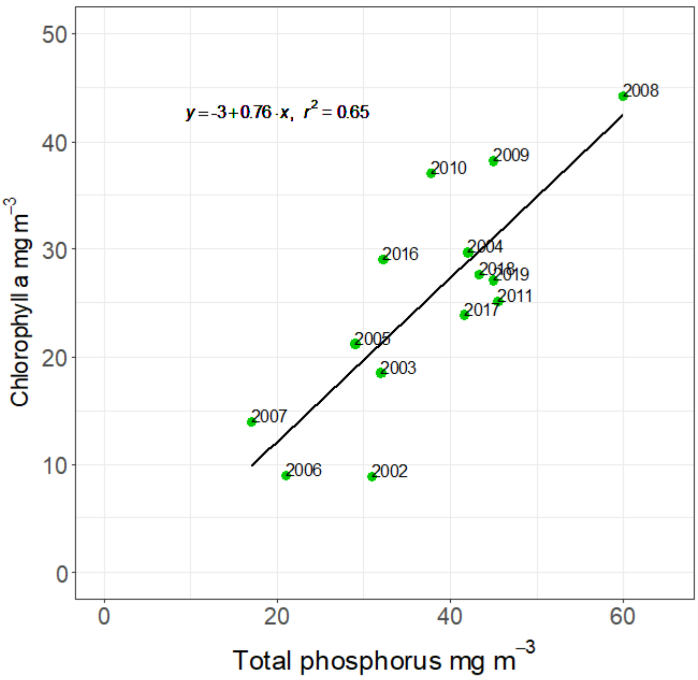

Figure 16: Chlorophyll-a (average of a two week period around day 250 - 7th September, CDRP V1.1.) and annual average total phosphorus.

5.2.4. Science Use case 4 Brownification in Scandinavian lakes

This use case quantifies and analyses the seasonal and long term trend of brownification, i.e. in the humic colour, for selected Scandinavian lakes. Boreal lakes are characterized by a high content of coloured dissolved organic matter (CDOM) derived from the degradation of plants which strongly influences lake colour. Increasing levels of CDOM have been observed during the last two decades for many lakes and streams in both northern Europe and North America. This change in colour is most probably caused by recovery from acidification, changes in land-use as well as climate change. The natural annual cycle of the CDOM usually starts with maximum values after snow/ice thawing and spring floods, and then usually slightly decreases over the season. High rainfall can also increase the level of organic matter during summer and autumn.

The core purpose of the use case is to assess brownification in the context of climate change. However, it will also be of key interest to national water authorities as colour is unaesthetic in drinking water and will increase drinking water production costs. A high content of organic matter in the distribution network also favours the growth of bacteria and prevents a proper disinfection process in the finished drinking water. Even though dissolved organic matter is not directly toxic for human consumption, if subject to chlorination it can lead to THMs (Trihalomethanes) which are potentially carcinogenic (Cantor et al., 2010).

Several Lakes_cci products are utilised in the case study. Lake colour and related water constituent products will be derived from LWLR. In addition, LIC is used to derive the timing of ice melting. The lake ECVs are combined to monitor the lake colour in conjunction with lake thawing and water level throughout the seasons and to investigate brownification dynamics in Scandinavian lakes. The selection of lakes was done based on availability of in-situ data. The evolution of the brownification over time is assessed by investigating the start of seasonal increase, intensity and the variability.

A key output will be an evaluation of trends over time in the context of climate change. Time series at measurement stations or from full lake estimates will be generated as a first assessment. With the help of temporal aggregation, these are turned into heatmaps as a first step, showing the evolution of the browning over months and years (e. g.Figure 1717, **Erreur ! Source du renvoi introuvable.**). Trend analyses of the time series will further give an indication of the extent of brownification filling a key knowledge gap and detailing implications and contextualising environmental change for terrestrial and aquatic habitats.

Initial analysis carried out an examination of the spectral signature and assignment to optical water types and found evidence of sensor dependent deviation that was forwarded for consistency analysis. The comparison with the results from the CCN consistency option showed the same indication of sensor dependent deviation for the same lakes. Out of ten lakes considered, four were suitable for further analysis. Experts mentioned that these four lakes are not known for intense brownification for the last two decades. Lake Mälaren is known for brownification since 1960 and this can not be analysed with the current time period of the CCI Lakes dataset. Nevertheless, a correlation between short term brownification due to intense rainfall events can be analysed with the calculated Forel Ule Value. This was validated with insitu measurements of CDOM (Figure 19). Furthermore, the Forel Ule Value was identified as suitable parameter for the watercolour analysis and a correlation with insitu CDOM was found.

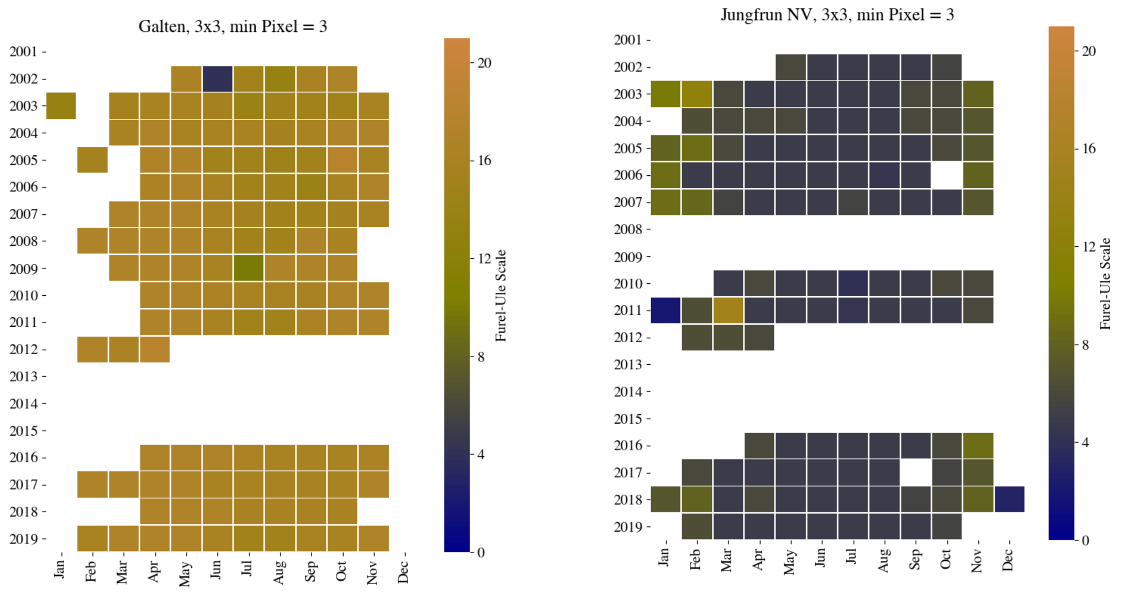

Figure 1717. Heatmaps of Lake colour (Forel-ULE, derived from LWLR) for two selected lakes in Sweden: left: Lake Galten (brown lake) and Lake Jungfrun (blue lake). Data from CDRP V1.1.

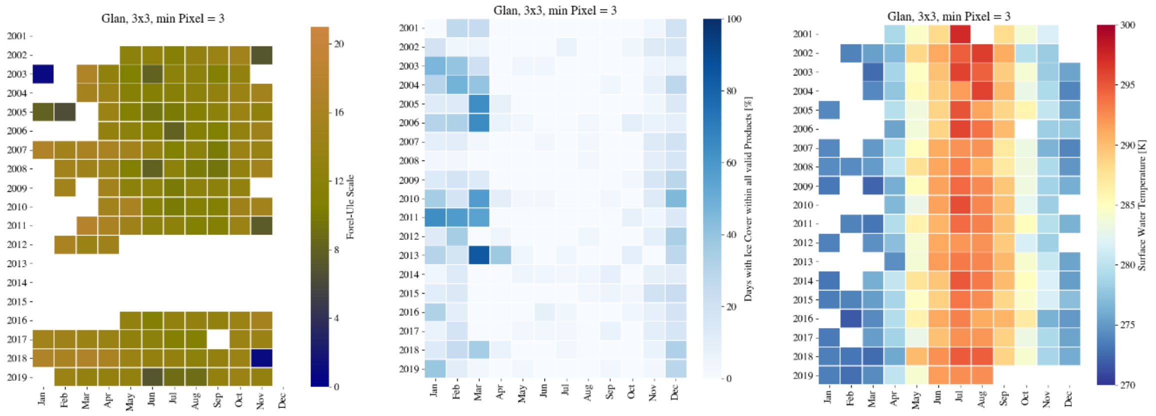

Figure 1818. Heatmaps of Forel_ULE (derived from LWLR), LIE ECV and LSWT ECV for Lake Glan in Sweden. Data from CDRP V1.1.

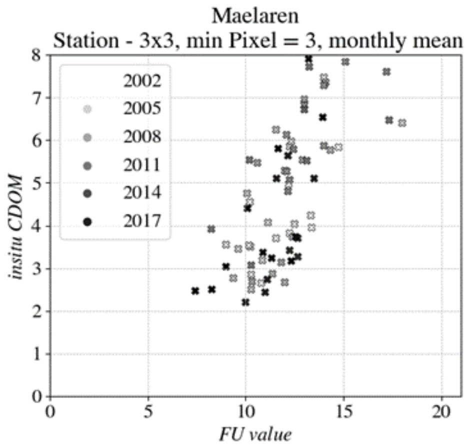

Figure 19: Scatterplot of Forel Ule Value (derived from 20CDRP V1.1) **and insitu CDOM for Lake Mälaren in Sweden.**

5.2.5. Science Use case 5 Consistency of ECVs in the Danube river-lake-lagoon

This use case validates the consistency of all variables in the Danube river-lake-lagoon system, particularly focusing on the highly dynamic Danube delta and connected Razelm Sinoe Lagoon System. The Razelm Sinoe Lagoon System water body covers about 1000 km^2 and consists of a series of former lagoons transformed into lakes (e. g. Razelm, Golovita, Zmeica) and present-day lagoons with engineered inlets (Sinoe Lagoon), as well as other lakes, ponds and wetlands. Hydromorphological alteration performed around the 1970's increased the connection with the Danube River. As a result, the original oligohaline environment rich in migratory fish (major spawning area for the NW Black Sea) was entirely transformed into a mainly freshwater body (with only Sinoe Lagoon remaining brackish). The change in salinity, water and sediment sources has deeply altered the ecosystems resulting in a fundamental change in the aquatic flora and fauna. The lagoon system has been granted the status of Biosphere Reserve (as part of the wider Danube Delta Biosphere Reserve) and has been improving in recent decades due to reduced nutrient loads.

The study area represents a clear example of dynamic and complex environmental change that serves as a challenging test for remote sensing studies. Water bodies from the lagoon system partly or entirely freeze during winter and undergo changes in suspended sediment load. In addition, the large evaporation rate in summer-autumn may also result in significant lake extension changes. The case study will therefore compare information from Lakes_cci on the temporal dynamics of LSWT, LIC, LWE (possibly LWL) and turbidity and chlorophyll-a from LWLR for all observable water bodies in the region and provide expert analysis of the consistency of these products.

GeoEcoMar has been studying the water and sediment dynamics in the Razelm-Sinoe lagoon system since early 2000 so a set of in-situ data is available for the following parameters: temperature, turbidity, and chlorophyll-a. This database is available for the Lakes_cci project for multiple proposes such as providing data for a comparison with satellite products. This activity is in progress and is focused on the two largest lakes of the investigated area: Razelm and Golovita. In situ data consist of a series of measurements of surface water temperature, chlorophyll-a and turbidity, from 2009 to 2018 (over 200 data points), collected over the lagoon, as well as higher frequency data collected at a fixed station seasonally (i. e. in November, March, May, July).

So far, an evaluation on time coverage of the lake variables was performed based on this dataset. More frequent data is available beginning with 2009 but major challenge for the Danube Delta area is cloud coverage, which can reduce satellite products usage of 50 % per year for LSWT, or even to 25 % per year for LWSR, in certain years. Overall, in this area, spring to autumn seasons have the most comprehensive time coverage of data sets.

Lakes_cci satellite products of chlorophyll-a and turbidity will also be analysed and compared to in-situ data and trend analysis will be performed on monthly averaged data. All ECV variables will be assessed in terms of time coverage of the satellite products and consistency, and time series analysis will be performed, assessing the time evolution of extremes as well as relationships between parameters.

This case study will exemplify how the lakes_cci variables can be utilised to separate climate and human impacts on river-lake-sea systems. It will provide feedback on the consistency and accuracy of the time-series within the context of the dynamics observed in the system. The use case will also allow the determination of the suitability of data formats for users less familiar with EO / geospatial data analysis providing feedback on the utility of data exploration, analysis tools and refining requirements for data sets with a regional focus through data aggregation. Lakes_cci data will also fill essential data gaps between field campaigns to corroborate (or otherwise) trends in the in situ data. For example, LSWT dynamics in surrounding lakes will provide a baseline to compare LSWT in the lagoon with both before and after closure of the lagoon to the sea, and will be related to ice-on and ice-off observations. This case study will also serve as an example to allow global upscaling follow-on studies for similar lake-lagoon systems.

Current work has focused on validation, comparing the results of Lakes_cci products with in-situ values for temperature, chlorophyll-a and turbidity. Significant relationships were found for all parameters across the range of Danube delta lakes examined. Trend analysis of seasonal values revealed mostly positive increases in temperature, turbidity and autumn chlorophyll (Figure 21) will incorporate additional lakes from the Danube Delta, available from version 2 of the CRDP, together with local metrological variables.

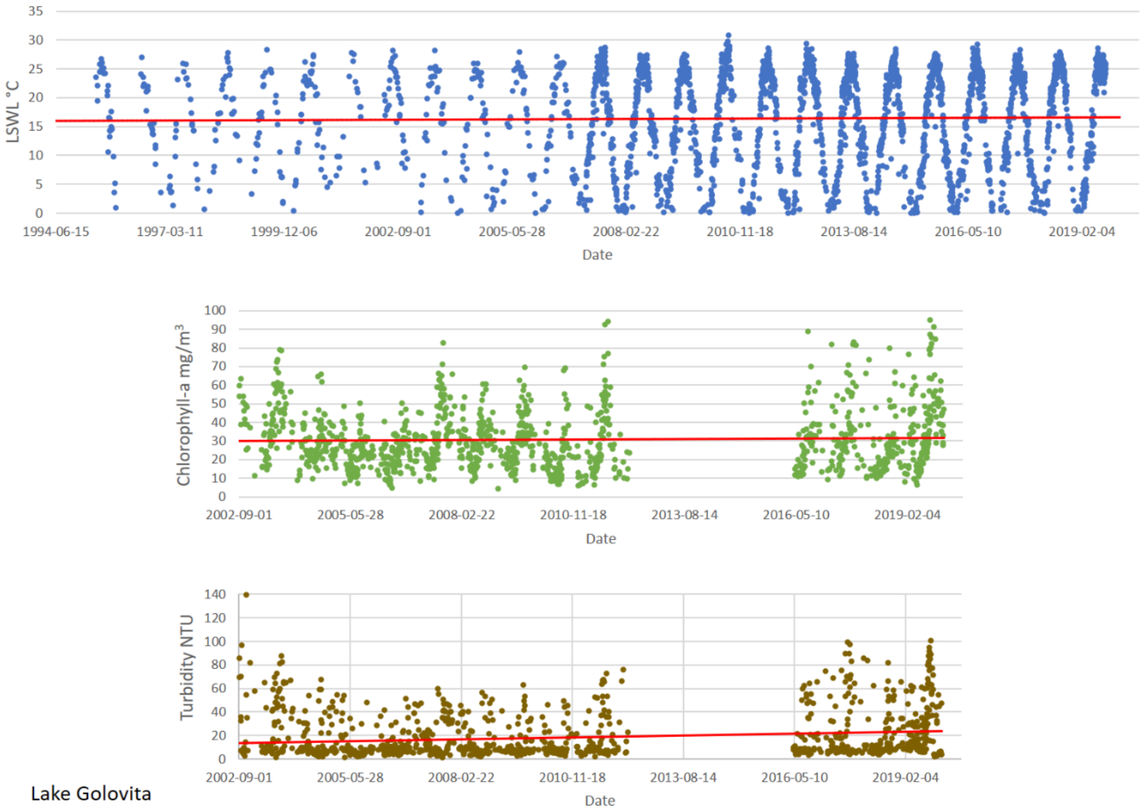

Figure 21: General trends for water temperature, chlorophyll-a and turbidity in Lake Golovita. Data from CDRP V1.1.

6. Progress in regard to user requirements

6.1. Product specification

This section details the progress made by Lakes_cci in meeting user requirements which are summarised in Table 1 with further detailed information available in the Product Validation and Intercomparison Report (PVIR), Product Specification Document (PSD) and End-to-End ECV Uncertainty Budget (E3UB). The algorithms selected for product generation are detailed in the Algorithm Theoretical Basis Document (ATBD) and has been driven by the requirements of the climate research community. In future iterations, a machine learning approach will be applied to LIC data and the methodologies for LWL will be further implemented to obtain a new product version in late 2021. Two methods for estimating the LWE were trialled – one supervised and one unsupervised approach. Key interferences were cloud cover and cloud shadow as well as definition issues regarding treatment of ice cover, wetlands and floating macrophyte stands. The LWE algorithm will be updated before the next CAR.

In Table 2, we specify observation target requirements for the Lakes ECV variables from the URD (reference: CCI-LAKES-URD-0019) and added a column to mark the respective status of achievement. Uncertainty and stability are quoted on a “1-sigma” basis (different to the GCOS presentation, so values are sometimes smaller). It is important to recap that this is a synthesis of target requirements and does not represent a statement of what will or can be achieved.

Table 2. Summary of target user requirements for the Lakes ECV ("1-sigma"). Thematic ECVs are Lake Water Level (LWL), Lake Water Extent (LWE), Lake Surface Water Temperature (LSWT), Lake Ice Cover (LIC), Lake Water Leaving Reflectance (LWLR). Sources are GCOS 2016 (G); Lakes_cci questionnaire (Q); project team's experience (P); literature review (L). In brackets and in italics secondary requirements. The last column indicates the achievement status for the first project year (red: not started, yellow: ongoing, green: completed).

Product	Parameter	Summary requirements	Source	*Status*
Measurement uncertainty	LWL	1. 5 cm for large lakes; 5 cm for the reminder	G	
Measurement uncertainty	LWE	5% (relative); 2. 5% (for 70 largest lakes)	G	
Measurement uncertainty	LSWT	0.15°K -0.20 °K	P	
Measurement uncertainty	LIC	10%	G, P	
Measurement uncertainty	LWLR	10-30% for peak waveband vs low signal bands; 0.1 mg m^{-3} chlorophyll-a and 1 g m^{-3} suspended matter.	P, L	
Stability	LWL	0.5 cm/decade	G	
Stability	LWE	2. 5% /decade	G	
Stability	LSWT	0.07°K per decade	P	
Stability	LIC/LWLR	1% /decade	G, P, L	
Spatial resolution	LWL/LWE	N/A: per lake	Q	
Spatial resolution	LSWT/LIC/LWLR	100 m	P	
Temporal resolution	LWL/LWE/LSWT/ LIC/LWLR	Daily observations	G, P, Q	
Length of record	LWL/LWE/LSWT/ LIC/LWLR	>10 years	L, P	
Maximum delay before availability of data (for climate users)	LWL/LWE/LSWT/ LIC/LWLR	>1 year	P	Not applica ble
Slicing of data	LWL/LWE/LSWT/ LIC/LWLR	Timeseries per lake	Q	
Spatial aggregation	LWL/LWE	Per-lake value	Q	
Spatial aggregation	LSWT/LIC/LWLR	Spatially resolved *(Per-lake value)*	Q	
Data format	LWL/LWE/LSWT/ LIC/LWLR	NetCDF *(GEOTIFF)*	Q	
Access	LWL/LWE/LSWT/ LIC/LWLR	FTP *(Web mapping service)*	Q	
Availability of uncertainty	LWL/LWE/LSWT/ LIC/LWLR	Required	Q	
Projection	LWL/LWE/LSWT/ LIC/LWLR	Regular latitude-longitude ("Level 3")	Q	

The five variables generated in the Lakes_cci project are derived from data from multiple instruments and multiple satellites. As a consequence, the temporal and spatial resolutions as well as data available for each component are not currently the same (Table 3). Nonetheless, the output is a consistent data format harmonised and supplied in the same temporal and spatial framework in NetCDF format. The dataset will be further harmonized in the next release of the Lakes_cci products as explained in the PSD.

Table 3. Current spatial and temporal resolution of each product

Product	Spatial Resolution*	Temporal Resolution	Temporal Coverage
LWL	N/A	1 to 10 days	1992 - present
LWE	10-30 m	1 to 10 days	1992 - present

Product	Spatial Resolution*	Temporal Resolution	Temporal Coverage
LIC	250 m	daily	2000 – present
LSWT	0.05 deg	daily	1995 - present
LWLR	300 – 1100 m	1-3 days	2002 - present

*Spatial resolution in meter refers to the nominal resolution at the equator, assuming the longitudinal and latitudinal pixel dimensions are similar), as is conventional in some domains and projections for land products. Resolution in degrees is the native sampling resolution.

Uncertainty estimates were provided for each product in unit of measure or percentage per pixel. Details on the procedures to derive uncertainty estimates were provided in the End-to-End Uncertainty Budgets report (E3UB). LSWT was separated into five quality levels with levels 4 and 5 being the best quality ensuring credible uncertainty. The validation of the LSWT shows very good mean agreement (comfortably within +/-0.2 K) between satellite LSWT and independent in situ temperature measurements. In 2021, work was also commenced on a specific package to examine consistency for the Lakes_cci variables. In particular, to address issues relating to known inconsistencies in ice classification between LIC and LWLR (resulting in unrealistic turbidity and chlorophyll-a). Other objectives are to exploit the synergy from daily LSWT, LIC and LWLR gridded products and to flag inconsistencies from dataset production.

From the first user survey useful information about the main scientific disciplines interested in Lakes_cci variables was obtained. It revealed that data will be mainly used for long-term analyses on climate change causes and effects, lake management and modelling. Easy data access, length of record and data on particularly important lakes are very useful factors in determining the use of Lakes_cci products. The first product release has matched these requirements. Certain targets are not fully completed, such as temporal or spatial resolution or uncertainty availability for all the variables, but this gap filling issue is being progressed as far as possible within the context of CDRP2.

The second user survey highlighted issues when using or merging the dataset, such as the need of pre-processing, of a stable temporal resolution without data gaps, and interoperability. Some concerns were also related to data format (i.e., global products, file size) identifying as desirable the option to download a sub-set of the data both spatially and temporally. Several users also suggested increasing the frequency and number of lakes, which will be achieved with the second version of the dataset (about 2000 lakes). In addition, a recent CMUG review of the suitability of CCI ECVs pointed out that users require high frequency data without gaps. They concluded that resources should be provided for post-processing and interpolation to produce spatially gridded data to include lake surface water temperature and lake ice (CMUG, 2020).

6.1.1. User workshop

The Lakes_cci User Workshop was organized in combination with the 6th workshop on “Parameterization of Lakes in Numerical Weather Prediction and Climate Modelling”, held in Toulouse, France, from 22nd to 24th October 2019. The “Parameterization of Lakes in Numerical Weather Prediction and Climate Modelling” takes place every second year and deals with lakes parameterizations Numerical Weather Prediction (NWP) and climate models. The principal aim of this common workshop was to exchange knowledge on lake remote sensing and on lake parameterization in climate models. The call for abstracts was hence oriented to receive contributions from the following topics:

- Modelling- Lake-atmosphere interactions and coupling (parameterization of lakes in numerical models of the atmosphere, the impact of lakes on atmospheric processes, greenhouse gases transfers). Processes in fresh-water bodies (including studies related to biochemistry and water quality issues, in frozen and non-frozen conditions) the lake-atmosphere interactions and coupling, and the processes in fresh-water bodies.
- Parameters- External parameters (raw data set and generation of external-parameter fields required to use lake parameterization schemes in atmospheric models, e. g. fields of lake depth and lake fraction).
- Data Assimilation- Snow and ice on lakes, reservoirs and other water bodies (Data assimilation of observations and parameterization of snow and ice layers over water surfaces in NWP and climate models, interaction air-snow-ice-water). Assimilation of observational data on lake surface state (space-borne and in-situ observations of lake surface state, assimilation of observational data into atmospheric models using lake parameterization schemes).
- Model validation and intercomparison - Validation of NWP models that incorporate lake parameterization and lake data assimilation schemes, single-column studies, intercomparison of lake models, e. g. within the framework of the Lake Model Intercomparison Project.
- Remote sensing can offer valuable data for studying lake changes and their interaction with their environment, and the impact and feedback of climate change. Altimeters provide dense time series of water surface elevation measurements and multispectral optical, thermal and radar sensors can be used to measure lake area, water quality, temperature, and ice cover. Time series of satellite products are available for developing studies on lake changes from local to global scale, e. g. within the framework of the CCI ECV LAKES.
- ISIMIP initiative: the aim of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) is to better understand climate impacts across sectors using a multi-impact model framework. The second phase of this international effort (ISIMIP2b) is designed to provide robust information about the impacts of 1. 5°C and 2°C global warming, as highlighted by the IPCC's special report on this topic. Scientists contributing simulations and analyses to ISIMIP will find a forum to exchange ideas at the workshop.

A total of 32 talks and 51 participants finally registered to the workshop before the deadline. The Lake-cci project was well represented with the participation of 8 people, four talks and two session chairs.

Several topics were highlighted at the beginning of the workshop. Among them, the value of LSWT (a satellite product already widely used within the community of modelers), and the question of how remote sensing and lake modelling communities can interact in the near future. In such a framework, the first question raised a point which could help link remote sensing (RS) and modelling groups is how to have a global extinction coefficient map for lake models? This is clearly an area where RS can help. The first guess would be to have a seasonal variation of this coefficient at the global scale. However, this would probably not be suitable for climate models, since seasonal variability of the extinction coefficient may not be representative of climate variability itself. RS can also help in ice coverage representation and more specifically to provide information when snow covers the ice (NWP purposes). Nonetheless, the areas where Lakes_cci can provide useful information to the modelling community are of course not limited but the extinction coefficient seems to be a good starting point. The community was also interested in river dammed reservoirs in temperate-arid zones, for which lakes_cci might provide valuable data, although lake size might be too small for some parameters.

7. Publications and outreach activities

In Table 4 and Table 5 the publications and meeting are reported.

Table 4. List of publications

Date	Type	Title	Authors	Title of the journal or equivalent
February 2019	Conference	Delivering the Lake Essential Climate Variables - an Update from ESA CCI Lakes	Duguay C. R., Crétaux J. F., Simis S., Merchant C. and Giardino C.	ASLO 2019 (abstract volume)
November 2019	Paper	Long-Term Water Surface Area Monitoring and Derived Water Level Using Synthetic Aperture Radar (SAR) at Altevatn, a Medium-Sized Arctic Lake	Vickers H., Malnes E. and Høgda K-A.	Remote Sens. 2019, 11(23), 2780 https://doi.org/10.3390/rs11232780
2020	Paper	Consistency of Satellite Climate Data Records for Earth System Monitoring	Popp et al.	Bulletin of the American Meteorological Society American Meteorological Society 101: E1948-E1971 https://doi.org/10.1175/BAMS-D-19-0127.1
2020	Paper	Climate velocity in inland standing waters	Woolway, R. I., & S. C. Maberly	Nature Climate Change 10: 1124-1129 https://doi.org/10.1038/s41558-020-0889-7
2020	Paper	River ice phenology and thickness from satellite altimetry. Potential for ice bridge road operation	Zakharova, E., S. Agafonova, C. Duguay, N. Frolova, & A. Kouraev,	The Cryosphere Discussions 2020: 1-31. https://doi.org/10.5194/tc-2020-325
2021	Paper	Assessment of machine learning classifiers for global lake ice cover mapping from MODIS TOA reflectance data	Wu, Y., C. R. Duguay, & L. Xu	Remote Sensing of Environment 253: 112206. https://doi.org/10.1016/j.rse.2020.112206

Date	Type	Title	Authors	Title of the journal or equivalent
2021	Paper	Detecting Climate Driven Changes in Chlorophyll-a in Deep Subalpine Lakes Using Long Term Satellite Data	Free, G., M. Bresciani, M. Pinardi, N. Ghirardi, G. Luciani, R. Caroni, and C. Giardino.	Water 13: 866. https://doi.org/10.3390/w13060866
2021	Paper	Phenological shifts in lake stratification under climate change	Woolway et al.	Nature Communications 12: 2318. https://doi.org/10.1038/s41467-021-22657-4
2021	Paper	Multivariate world-wide lake physical variable timeseries for climate studies	L. Carrea (UoR), B. Calmettes (CLS) et al.	Scientific Data (Nature) (In Preparation)
2021	Book chapter	Optical remote sensing in shallow lake Trasimeno: understanding from applications across diverse temporal, spectral and spatial scales	Bresciani, M., G. Free, M. Pinardi, M. Laanen, R. Padula, A. Fabbretto, S. Mangano, & C. Giardino	Springer "Water" book series. (Accepted)
2021	Paper	Using remote sensing to understand the influence of climate change on bloom dynamics in a shallow eutrophic lake	Free, G., M.Bresciani M. Pinardi, S. Peters, M. Laanen, R. Padula, A.Cingolani F.Charavgis, & C. Giardino	Hydrobiologia (Under review)

Table 5. List of meetings

Conference	Dates		Place	CCI Lakes Attendees	Comment
CMUG 18	10/29/18	10/31/18	Exeter, UK	C. Giardino S. Simis	Oral
ASLO	23/02/19	02/03/19	San Juan, Puerto Rico	C. Duguay	Oral
CCI colocation meeting	26/03/19	28/03/19	Oxford, UK	S. Simis B. Coulon C. Merchant B. Calmettes	Poster

Conference	Dates		Place	CCI Lakes Attendees	Comment
ESA Living Planet Symposium	13/05/19	17/05/19	Milan, Italy	C. Giardino S. Simis J. F. Crétaux L. Zawadzky C. Duguay Hervé Yesou K. Seltzer	Poster
9th session of the GTN-H Meeting	25/09/19	27/09/19	Koblenz	L. Zawadski/B. Calmettes	Project Presentation to GTN-H committee
6th Lake Workshop on Parameterization of Lakes in NWP and Climate Modelling	22/10/19	24/10/19	Toulouse, France	C. Duguay Claudia J. F. Crétaux S. Simis B. Calmettes A. Tylor	Posters and presentations (link: http://www. meteo. fr/cic/meetings/19/LAKE19/)
CMUG 19	06/11/19	07/11/19	Barcelona, Spain	C. Giardino, C. Merchant	Poster
OSTST	21/10/19	25/10/19	Chicago (US)	L. Zawadski	Poster + Oral
ClimRisk19 | Climate Risk: implications for ecosystem services and society, challenges, solutions	23/10/19	25/10/19	Trento, Italy	M. Pinardi (CNR)	Poster (link: http://www. sisclima. it/conferenza-annuale-19/?lang=en)
Night of Ideas, Living Earth	26/2/20	26/2/20	Baku, Azerbaïdjan	JF. Cretaux	Oral presentation "Modern space technologies to understand the effects of climate change on planet Earth" Conference in French
IGARSS 20	26/9/20	2/10/20	Virtual meeting	Y. Wu (H2O)	Wu, Y., C.R. Duguay and L. Xu, 20. Lake ice classification from MODIS TOA reflectance imagery using a convolutional neural network: a case study of Great Slave Lake, Canada.
GLEON 21.5	19/10/20	22/10/20	Virtual meeting	G. Free (CNR)	Poster
CLIMRISK20: TIME FOR ACTION!	21/10/20	23/10/20	Virtual meeting	M. Pinardi (CNR)	Poster

Conference	Dates		Place	CCI Lakes Attendees	Comment
EO4Polar science	28/10/20	30/10/20	Virtual meeting	E. Malnes (NORCE)	
CMUG	9/20	9/20			
CCI Co-location meeting	9/9/20	11/9/20	Virtual meeting		
EO4Water Cycle 20	16/11/20	18/11/20	Versailes (France)	LEGOS, CLS, SERTIT, CNR	Oral Presentation: Lake Water Levels: From Topex/Poseidon to Sentinel-3. From R&D to operational products Posters: • Benchmarking_of_LWE_Extraction_Methods_Based_on_HR_Optical_and_SAR_Sentinel_data_Exploitation_in_the_CCI_Lakes_Framework • Creating the first consistent record of Lakes essential climate variables
10th International Shallow Lakes Conference 2021	1/3/21	5/3/21	Virtual meeting	M. Bresciani (CNR)	
Climate Science Working Group (CSWG): Fire, HRLC, LC and Biomass	18/1/21	18/1/21	Virtual meeting	C. Giardino, G. Free (CNR)	
Climate Science Working Group (CSWG): Lakes, Snow and Permafrost ECVs	7/5/2021	7/5/2021	Virtual meeting	JF Creteaux (LEGOS),	CCI Lakes presentation
EGU 2021	19/4/21	30/4/21	Virtual meeting	C. Giardino, G. Free (CNR)	Poster & lightning talk: The essential climate variables for lakes: exploring satellite products from global to local scale

Conference	Dates		Place	CCI Lakes Attendees	Comment
From Science to Operations for Copernicus Imaging Microwave Radiometer (CIMR) Mission	10/05/21	12/05/21	Virtual meeting	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	7/06/21	11/06/21	Virtual meeting	C. Duguay (H2O)	Oral presentation: Duguay, C.R., G. Picard, E.A. Zakharova, J. Murfitt, M. Restano, and J. Benveniste, 2021. 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	7/06/21	11/06/21	Virtual meeting	A. Mangilli (CLS)	Poster presentation: Mangilli, A., C. Duguay, E. Zakharova, A. Kouraev, and P. Thibaut, 2021. 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	7/06/21	11/06/21	Virtual meeting	JF. Crétaux (LEGOS) B.Calmettes (CLS) H. Yesou (SERTIT)	JF. Crétaux, B. Calmettes, Muriel Bergé-Nguyen : Lake Water Levels: From Topex/Poseidon to Sentinel-3. From R&D to operational products. B. Calmettes, JF. Crétaux, V. Vuglinsky, A. Lopez Gutierrez. Validation of lake water level estimated by altimetry compared to in situ measurements H. Yésou, E. Malnes, P. Blanco, T. Ledauphin, H. Ming Siu Vickers, M. Berge-Nguyen, J. Maxant, JF Cretaux, B. CouloEnvironmental effects on methods' benchmarking: Chad Archipelago exploiting HR optical and SAR Sentinel data in the CCI Lakes framework
AIOL	30/06/21	7/02/21	Virtual meeting	G. Free (CNR)	Oral presentation: Detecting climate driven changes in chlorophyll-a in deep subalpine lakes using long term satellite data

Conference	Dates		Place	CCI Lakes Attendees	Comment
AIOL	30/06/21	07/02/21	Virtual meeting	M. Bresciani (CNR)	Poster and lightning talk: Analysis of global satellite products for the Essential Climate Variable 'Lakes' in the LTER framework
SEFS12	25/7/21	30/7/21	Virtual meeting	G. Free (CNR)	abstract submitted

Future outreach activities:

If a suitable use of data for a selection of LTER sites is demonstrated it will be key to contact and raise awareness of the dataset – many research institutes carry very broad dynamic ecological and ecosystem research on fish, invertebrates, phytoplankton, zooplankton, macrophytes presenting an enormous research opportunity for data use. Often there are large research institutes associated with big lakes- usually associated with a lakes importance for recreation and tourism.

Results from the UCS will be described in a scientific publication (target journal: Limnology and Oceanography). Results will be disseminated also through the DANUBIUS-RI project which features the Danube delta as one of several super-sites for in situ and EO monitoring throughout Europe, communicating EO benefits and in-situ data optimization opportunities (e. g. site selection). Additional outreach activities will continue to highlight the upcoming availability of CDRP2 at international conferences e.g. SEFS12.

8. Conclusions

Lakes are especially vulnerable to climate change. Variations in temperature and precipitation can profoundly affect the hydrological functioning of the lake and its catchment. Together with changes in ice formation, lake level, lake shrinking and hydrogeochemistry the effect on lake ecological functioning can be significant (Adger et al., 2007; Cisneros et al., 2014; Sala et al., 2000). Recently, Woolway et al. (2020) outlined how future efforts investigating lake responses to climate change need to be grounded in sustainable, systematic, multivariate observations for a consistent set of lakes. The authors outlined how one effort in this direction relies on this Lakes_cci project, which coordinates a range of remote- sensing techniques to address the lake ECVs identified by the GCOS. The project has now released the first version (1.0) of merged satellite products (Crétaux et al., 2020) and this document presents a first investigation of the products.

This report describes an initial description of the CRDP V1.1 and provides a first global overview on data distribution with some basic plots indicating the range of variation for the set of investigated variables. Such investigation allowed the team to familiarize with the products and with coding to extract the five variables according to recommendations (e. g. on uncertainties, quality levels) from the PUG and the PSD documents. Each use case also outlined the basic structure being followed to perform the activities of the five specific topics covering a set of key studies on: i) how lakes are responding to climate change in regions which are highly susceptible to global warming, ii) the brownification process of boreal lakes, cross-ECVs analysis from iii) local systems to iv) large lakes at global scale, and v) studies in which satellite products are combined with long term in situ observations for different lakes across the globe. Furthermore, thoughts on potential links and analysis with other climatic datasets has been outlined in view of synergic activities under the wide umbrella of the ESA CCI framework.

However, it is necessary to remember that this is the second version of CAR and is therefore limited in both in the CRDP analysis and in use-case results that are currently ongoing to derive conclusions on how lakes are responding to climate change. Therefore, the CRG has to perform most of the activities in the next months, to also develop the use cases and to prepare scientific publications. To this end, some suggestions to the project team have been identified and acted upon such as the generation of color indexes (e. g. Forel HUE) from LWLR, or the need to cover parts of the Earth not included in the CRDP V1.1 (e. g. New Zealand). The second version of the CRDP is in preparation and will include up to 2000 lakes improving coverage spatially while improvements to algorithms and the addition of new satellites will improve data quality and temporal frequency. In addition a work package to improve consistency across the lake variables has been instigated. The project team continues to work to disseminate the Lakes_cci products by attending conferences, by preparing manuscripts and, last but not least, by promoting the dataset in different communities (e.g. IOCCG). We definitely believe that as soon a wide group of experts will look at these data some important results will be found independent of our own work.

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• Annex - Project Acronyms

This is a generic list containing all the acronyms used in the project

AATSR	Advanced Along Track Scanning Radiometer
AERONET-OC	AErosol RObotic NETwork - Ocean Colour
AMI	Active Microwave Instrument
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
APP	Alternating Polarization mode Precision
ASAR	Advanced Synthetic Aperture Radar
ASLO	Association for the Sciences of Limnology and Oceanography
ATBD	Algorithm Theoretical Basis Document
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced very-high-resolution radiometer
BAMS	Bulletin of the American Meteorological Society
BC	Brockman Consult
C3S	Copernicus Climate Change Service
CAR	Climate Assessment Record
CCI	Climate Change Initiative
CDR	Climate Data Record
CEDA	Centre for Environmental Data Archival
CEMS	Centre for Environmental Monitoring from Space
CEOS	Commitee on Earth Observation Satellites
CGLOPS	Copernicus Global Land Operation Service
CIS	Canadian Ice Service
CLS	Collecte Localisation Satellite
CMEMS	Copernicus Marine Environment Monitoring Service

CMUG	Climate Modelling User Group
CNES	Centre national d'études spatiales
CNR	Compagnie Nationale du Rhône
CORALS	Climate Oriented Record of Altimetry and Sea-Level
CPD	Communication Plan Document
CR	Cardinal Requirement
CRDP	Climate Research Data Package
CRG	Climate Research Group
CSWG	Climate Science Working Group
CTOH	Centre for Topographic studies of the Ocean and Hydrosphere
DUE	Data User Element
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
ELLS-IAGRL	European Large Lakes Symposium-International Association for Great Lakes Research
ENVISAT	Environmental Satellite
EO	Earth Observation
EOMORES	Earth Observation-based Services for Monitoring and Reporting of Ecological Status
ERS	European Remote-Sensing Satellite
ESA	European Space Agency
ESRIN	European Space Research Institute
ETM+	Enhanced Thematic Mapper Plus
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAQ	Frequently Asked Questions
FCDR	Fundamental Climate Data Record
FIDUCEO	Fidelity and Uncertainty in Climate data records from Earth Observations
FP7	Seventh Framework Programme
GAC	Global Area Coverage
GCOS	Global Climate Observing System
GEMS/Water	Global Environment Monitoring System for freshwater
GEO	Group on Earth Observations
GEWEX	Global Energy and Water Exchanges
GloboLakes	Global Observatory of Lake Responses to Environmental Change
GLOPS	Copernicus Global Land Service
GTN-H	Global Terrestrial Network – Hydrology

GTN-L	Global Terrestrial Network – Lakes
H2020	Horizon 2020
HYDROLARE	International Data Centre on Hydrology of Lakes and Reservoirs
ILEC	International Lake Environment Committee
INFORM	Index for Risk Management
IPCC	Intergovernmental Panel on Climate Change
ISC	International Science Council
ISO	International Organization for Standardization
ISRO	Indian Space Research Organisation
JRC	Joint Research Centre
KPI	Key Performance Indicators
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
LIC	Lake Ice Cover
LSWT	Lake Surface Water Temperature
LWE	Lake Water Extent
LWL	Lake Water Level
LWLR	Lake Water Leaving Reflectance
MERIS	MEdium Resolution Imaging Spectrometer
MGDR	Merged Geophysical Data Record
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	MultiSpectral Instrument
MSS	MultiSpectral Scanner
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NSERC	Natural Sciences and Engineering Research Council
NSIDC	National Snow & Ice Data Center
NTU	Nephelometric Turbidity Unit
NWP	Numerical Weather Prediction
OLCI	Ocean and Land Colour Instrument
OLI	Operational Land Imager
OSTST	Ocean Surface Topography Science Team
PML	Plymouth Marine Laboratory
PRISMA	PRecursore IperSpettrale della Missione Applicativa
Proba	Project for On-Board Autonomy
R	Linear Correlation Coefficient

RA	Radar Altimeter
RMSE	Root Mean Square Error
SAF	Satellite Application Facility
SAR	Synthetic Aperture Radar
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SIL	International Society of Limnology
SLSTR	Sea and Land Surface Temperature Radiometer
SoW	Statement of Work
SPONGE	SPaceborne Observations to Nourish the GEMS
SRD	System Requirements Document
SSD	System Specification Document
SST	Sea Surface Temperature
STSE	Support To Science Element
SWOT	Surface Water and Ocean Topography
TAPAS	Tools for Assessment and Planning of Aquaculture Sustainability
TB	Brightness Temperature
THM	Trihalomethane
TM	Thematic Mapper
TOA	Top Of Atmosphere
TR	Technical Requirement
UNEP	United Nations Environment Programme
UoR	University of Reading
US	United States
VIIRS	Visible Infrared Imaging Radiometer Suite
WCRP	World Climate Research Program
WFD	Water Framework Directive
WHYCOS	World Hydrological Cycle Observing Systems
WMO	World Meteorological Organization
WP	Work Package