Lakes_cci+ Phase2

D4.3. Product User Guide (PUG)

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1 Introduction

1.1 Scope

This Product User Guide (PUG) contains a description of the Lakes_cci Climate Research Data Package (CRDP) version 2.1.0. This dataset was produced as part of the European Space Agency (ESA) Climate Change Initiative. The PUG provides users with practical information regarding the content and recommended use of the Lakes Essential Climate Variable (ECV) products included in this dataset.

The overarching objective of the Lakes_cci project is to produce and validate a consistent data set of the variables grouped under the Lakes ECV. This includes aiming for the longest period of combined satellite observations by operating processing chains for suitable satellite imagery, ultimately featuring in a sustainable production system. This PUG details the contents, format, and standards applied to the files that make up the dataset. It also introduces some software tools that can help new users explore the data contained in the CRDP.

The Lakes ECV covers: Lake Water Level, Lake Water Extent, Lake Surface Water temperature, Lake Ice Cover, Lake Ice Thickness and Lake Water-Leaving Reflectance.

The specific objectives for the Lakes_cci project are:

- **To assess** the requirements of the climate research community and thereby ensure consistency in the (further) development of the Lakes ECV processing system.
- **To develop**, test and select the best algorithms and standards to produce high quality Lake products for climate applications across sensors.
- **To provide** a specification of the operational production system, aligned with related activities in the Copernicus programme (e.g. Global Land Service, C3S). Algorithms are developed or improved to meet user requirements.
- **To validate** the Lake ECV products through independent climate research groups and use cases.
- **To generate** new interest in the EO climate datasets produced for inland water bodies within the community of limnologists, operating at local to global spatial scales and likely to use varying subsets of the Lakes ECV products.

1.2 Dataset

Lakes are of significant interest to the scientific community, local to national governments, industries and the wider public. A range of scientific disciplines including hydrology, limnology, climatology, biogeochemistry and geodesy are interested in the distribution and functioning of the millions of lakes (from small ponds to inland seas) from the local to the global scale. Remote sensing provides an opportunity to extend the spatio-temporal scale of lake observation, within the observational limitations set by the available satellite sensors.

The Lakes_cci develops products for the following six thematic climate variables:

- Lake Water Level (LWL): to understand the balance between water inputs and water loss.
- Lake Water Extent (LWE): a proxy for change in glacial regions (lake expansion) and drought in many arid environments, relating to local climate for the cooling effect that water bodies provide.
- Lake Surface Water temperature (LSWT): correlated with regional air temperatures and a proxy for mixing regimes, driving biogeochemical cycling and seasonality.
- Lake Ice Cover (LIC): freeze-up in autumn and advancing break-up in spring are proxies for gradually changing climate patterns and seasonality.

- Lake Ice Thickness (LIT): a proxy indicator of changes in air temperature and on-ice snow mass (depth and density) during the ice growth period.
- Lake Water-Leaving Reflectance (LWLR): a direct indicator of biogeochemical processes and habitats in the visible part of the water column (e.g. seasonal phytoplankton biomass fluctuations) and an indicator of the frequency of extreme events (peak terrestrial run-off, changing mixing conditions).

In this context, Lakes_cci represents a unique framework to provide **consistent and homogenous** data to the multiple communities of lake scientists. The project actively engages with this community to assess the utility and future improvement of Lakes_cci products.

Key considerations for the Lakes ECV dataset are based on the combined requirements from user communities and the Global Climate Observation System (GCOS) targets. These considerations are summarised in the next chapter and detailed in the User Requirements Documentation (URD). As a rule of thumb, the Lakes ECV makes use of those satellite sensors which can be calibrated to the best available standards, for the longest legacy of sensors possible. Modern sensors generally offer better resolution and sensitivity than legacy sensors, whilst the Lakes ECV datasets are on a harmonized grid resolution. This trade-off determines the size range of observable lakes, which just over 2000 lakes currently targeted at a resolution of 1/120 degree (nominally 1 km), with all available data provided in daily aggregation periods. The water extent, water level and ice thickness products are not provided across the whole lake but derived for the lake as a whole from narrow satellite tracks. Details of the data set are provided in Section 0, whilst the full methodology is described in the Algorithm Theoretical Basis Document (ATBD).

Version 2.1 of the Lakes_cci dataset nominally covers the period 1992-2022, where suitable sensors were available.

1.3 Requirements

A user requirements analysis was conducted to design the specification of the lakes_cci product to best address the needs of key users. The approach involved a review of existing requirements specified by ESA and the Global Climate Observing System (GCOS). User requirements have been further refined through an online survey, open to both current and potential users of the ECV Lakes for both climate and more general applications.

Table 1 shows the observation target requirements for the Lakes ECV products. The general method of synthesis for these targets is to adopt the most stringent well-justified statement of requirement. The synthesis is therefore a statement of target requirements and not of what will or can be achieved.

Table 1: Synthesised observation target requirements for the Lakes ECV. The source of the requirements is indicated in parentheses as follows: G: GCOS (2022 - Threshold), Q: Lakes_cci questionnaire, P: project team expertise, L: literature review.

Product	Lake Water Level (LWL)	Lake Water Extent (LWE)	Lake Surface Water Temperature (LSWT)	Lake Ice Cover (LIC)	Lake Ice Thickness (LIT)	Lake Water Leaving Reflectance or Lake Colour (LWLR)
Measurement uncertainty	10 cm (G)	5% (relative) (G)	0.2°K (P)	LIC: 10% (G,P)	15 cm (G)	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.

Product	Lake Water Level (LWL)	Lake Water Extent (LWE)	Lake Surface Water Temperature (LSWT)	Lake Ice Cover (LIC)	Lake Ice Thickness (LIT)	Lake Water Leaving Reflectance or Lake Colour (LWLR)
Stability	10 cm/decade (G)	5% /decade (G)	0.07°K per decade (P)	LIC: 1% /decade (G)	10 cm/decade (G)	1% /decade (G,P,L)
Spatial resolution	N/A : per lake (Q)	N/A : per lake (Q)	1000 m (P)	LIC: 100 m (P)	10000 m (G)	100 m (P)
Temporal resolution	daily ground-based or satellite observations (G)	30 days (G)	Daily (P)	LIC: 3-7 days (G,P)	365 days (G)	Daily observations (Q)
Length of record	>10 years (L)	>10 years (L)	>10 years (L)	>10 years (L)	>10 years (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)

2 Instruments overview

Observation data from multiple satellite missions are required for the successful generation and validation of all component products for the Lakes ECV.

Table 2 summarises the satellite/sensor used in the estimation of the products that are part of the Lakes ECV. The user is advised to refer to the CRDP metadata to see which satellite/sensors are used for a given observation.

Table 2. Missions and instruments used in the generation of the Lakes_cci dataset.

Satellite	Sensor	Product					
		LWL	LWE	LSWT	LIC	LIT	LWLR
Topex/Poseidon	Poseidon-1	X					
Jason-1	Poseidon-2	X				X	
Jason-2	Poseidon-3	X				X	
Jason-3	Poseidon-3B	X				X	
Sentinel-6A	Poseidon-4	X				X	
ENVISAT	Radar Altimeter (RA-2)	X					
	AATSR			X			
	MERIS						X
SARAL	AltiKa	X					
Geosat Follow On	Radar Altimeter	X					
Sentinel-1	C-band SAR		X				
Sentinel-2	MSI		X				
Sentinel-3A/B	SRAL	X					
	OLCI A/B						X
	SLSTR		X	X			
Landsat-4	MSS, TM		X				

Satellite	Sensor	Product					
		LWL	LWE	LSWT	LIC	LIT	LWLR
Landsat-5	MSS, TM		■				
Landsat-7	ETM+		■				
Landsat-8	OLI		■				
Terra/Aqua	MODIS			■	■		■
ERS-1	RA						
	AMI		■				
	SAR		■				
ERS-2	RA	■					
	AMI		■				
	SAR		■				
	ATSR-2			■			
METOP-A/B	AVHRR			■			

3 Data Description

3.1 Lake Water Level (LWL)

3.1.1 LWL definition and usage

LWL refers to the lake water level above a reference geoid. Radar altimetry from space consists of vertical range measurements between the satellite and water level. The water level is determined as the difference between the satellite altitude above a reference surface (usually a conventional ellipsoid and then a geoid), determined through precise orbit computation, and satellite-water surface distance. Placed onto a repeat polar orbit, the altimeter satellite passes a given region at regular time intervals (called the orbital cycle), thus completing its coverage of the Earth.

Water level measurement by satellite altimetry was initially developed and optimised for open oceans. Nevertheless, the technique is now applied to obtain water levels of inland seas, lakes, rivers, floodplains, and wetlands.

3.1.2 LWL data characteristics

The LWL product is composed of three variables: the water level estimation, its associated uncertainty and any quality flags for the measurement. The details for the estimation of those variables are fully described in the ATBD (Algorithm Theoretical Basis Document). The LWL product is generated at irregular time steps, depending on which satellites pass over the target. For harmonisation with the other Lakes ECV products, the LWL result is duplicated onto the grid for the nominal lake area, derived from its maximum water extent. Thus, when plotting time-series of LWL for a given lake, it is sufficient to pick one data point within the lake from the gridded dataset.

The LWL product covers a period of more than 30 years, from the first altimetry mission Topex/Poseidon launch in 1992 until the current missions: Sentinel-3A, Sentinel-3B and Sentinel-6A.

3.1.3 LWL data sources

Several satellite altimetry missions have operated since the early 1990s (Table 3) : ERS-1/RA (1991-1996), TOPEX/Poseidon (1992-2006), ERS-2/RA (1995-2005), GFO (2000-2008), Jason-1 (2001-2012), ENVISAT/RA-2 (2002-2012), Jason-2 (2008-2018), Jason-3 (2016-2022), Sentinel-6A (2021-), Cryosat-2 (2010-), HY-2A (2011-), SARAL/AltiKa (2013-), Sentinel-3A (2016-), and Sentinel-3B (2018-).

ERS-1, ERS-2, ENVISAT and SARAL have a 35-day temporal resolution (duration of the orbital cycle) and 70 km inter-track spacing at the equator. TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3 have a 10-day orbital cycle and 350 km equatorial inter-track spacing. GFO has a 17-day orbital cycle and 170 km equatorial intertrack spacing. The Sentinel-3A orbit has a revisit time of 27 days and its inter-tracking separation is 104 km. This has been reduced to 52 km in a two-satellite configuration (Sentinel-3A and B). Lake Water levels are based on merged multi mission observations. As a result, the combined global altimetry data set has almost 30 years history for many lakes and is intended to be continuously updated in the coming decade. Combining altimetry data from several in-orbit altimetry missions increases the space-time resolution of the sensed hydrological variables.

Table 3. Altimetry missions

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Topex/Poseidon	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																
Jason-1									■	■	■	■	■	■	■	■	■	■	■	■	■										
Jason-2																	■	■	■	■	■	■	■	■	■	■	■				
Jason-3																											■	■	■	■	■
Sentinel-6A																														■	■
ERS-2				■	■	■	■	■	■	■	■	■	■	■																	
ENVISAT											■	■	■	■	■	■	■	■	■	■	■										
Cryosat-2																			■	■	■	■	■	■	■	■	■	■	■	■	■
Sentinel-3A																									■	■	■	■	■	■	■
Sentinel-3B																											■	■	■	■	■
GFO									■	■	■	■	■	■	■	■	■														
HY-2A																				■	■	■	■	■	■	■	■	■	■		
SARL/Altika																						■	■	■	■	■	■	■	■	■	■

3.1.4 LWL data limitations

An important aspect concerns spatial coverage, as lake water levels can not be estimated for all the lakes in the target polygons, given that 397 are not covered by altimetry missions. In addition, each lake must be analysed independently in order to assess the optimum parameters for generating the timeseries. This activity, that is time consuming and needs the estimation of multiple inter mission and inter tracks bias, is not necessarily successful. In some cases, for landscape configuration or satellite operating mode, the quality of the timeseries is not good enough to be included in the dataset.

Additionally, the timestep for LWL product is lake dependent. It is determined by the altimetry missions observing the lake and the repetitivity of these missions. For example, for lakes observed by a single track of Sentinel-3A, a measurement is provided every 27 days. For larger lakes, observed by more than one mission and track, the time step may be daily.

Another limitation concerns the location of the track over the lake, providing a variable number of level 2 measurements used for the estimation of the level 3. The number of level 2 measurements contributes directly to the estimation of the Level 3 uncertainty.

Finally, we consider that the water level is the same throughout all the lake. This assumption is true for most of the lakes. Nevertheless, for very large lakes, this value may vary due to factors as wind or tides.

3.2 Lake Water Extent (LWE)

3.2.1 LWE definition and usage

LWE can be expressed as the presence of water (on a map), or as the total areal extent of a waterbody (a single number). In the Lakes_cci, the latter approach is used. Studying and monitoring variations and trends in lake area, or lake water extent (LWE) can identify climatic variations over time, because LWE is sensitive to changes in the water cycle and heat balance. LWE together with LWL can be used to assess the total volume of water in a lake (Arsen et al., 2014; Cretaux et al., 2016; Nikraftar Z. and Azizia A., 2015; Busker at., 2019; Sima et al., 2013; Ryan et al., 202).

The solution to determining lake water extent variations for a large number of lakes globally is to delineate lake shorelines from satellite imagery. In the Lakes_cci we use high resolution optical imagery, ie Sentinel–2 like, to determine the lake extent, which is then combined with lake water level observations from radar altimetry to determine a hypsometry relationship. This relationship represents the variation of lake extent with respect to lake height. When the hypsometry of a lake is established, water height and extent of lakes can be determined simultaneously from altimetry without the need to analyse a prohibitively large volume of high-resolution optical imagery. The results can be provided from daily (for large water bodies) to weekly or monthly, depending on the lake location and satellite track.

3.2.2 LWE data characteristics

LWE are generated both as a geocoded binary map (water/non water) in geotiff and shapefile and as a single area value (in square kilometres) in a text file. Pixel size depends on the employed images. Uncertainty information will be provided with these products. At the present time the generation of this information is under development.

For a better understanding of the LWE product, it is worth mentioning some characteristics of the optical images and the followed methodology (detailed in the ATBD document) : The use of optical data for water delineation is based on the analysis of the reflected signal. Depending on the lake type, ie deep, shallow, very shallow, the reflected signal will differ with a more or less influence of the lake bottom. It will also depend on the presence of dissolved materials, floating or submerged vegetation. Moreover, the conditions of acquisitions would also influence the signal, i.e. sun-glint case.

3.2.3 LWE data sources

The optical default sensor employed in this project is Sentinel–2. In complement, Landsat data could be exploited in order to cover hydrological specific conditions, i.e. extremes ones, during older period, up to the mid 90' with Landsat 5. In any case, any optical HR mission image can be used to retrieve LWE according to the methodologies developed and employed in the present project.

3.2.4 LWE data limitations

First limitation is related to the classical presence of clouds coverage, more or less dense. This is particularly true for some lakes in tropical areas with high cloud cover, this is in general hard to collect enough optical satellite images, particularly during the wet seasons. Moreover, for some very large lakes, classical optical images do not allow covering the whole surface of the lake, hence leading to collect several images, but this purpose is not easily achievable since images must be collected at the same dates.

In addition, the LWE extraction can be limited/disturbed by the presence of elements on the water surfaces, such as ice, floating/§submerged vegetation, as well as acquisition's conditions (sun-glint)

Finally, the procedure adopted for LWE, which is based on the hypsometry's method, is time consuming and can be performed only lake per lake, with visual checking, although many steps of the procedure have been automized.

3.3 Lake Ice Cover (LIC)

3.3.1 LIC definition and usage

LIC refers to the extent (or area) of a lake covered by ice. Lake-wide ice phenology can be derived from LIC, including freeze onset to complete freeze over (CFO) dates during the freeze-up period, melt onset to water clear of ice (WCI) dates during the break-up period, and ice cover duration between CFO and WCI dates over an ice year (Duguay et al. 2015). For lakes that do not form complete ice cover every year or in some years (e.g. Laurentian Great Lakes of North America), maximum ice cover extent (as a function of time) is also a useful climate indicator that can be determined (Derksen et al. 2019). Similarly, the minimum ice cover extent (as function of time) can be derived for High Arctic lakes that do not completely lose their ice cover in summer, although a recent study suggests that these lakes may be transitioning from perennially to seasonally ice-covered (Surdu et al. 2016). Knowledge of fractional ice coverage (expressed as a percentage of total area of a lake covered by ice) on a daily to weekly basis is also useful for improving numerical weather forecasting in regions where ice cover forms.

LIC is highly sensitive to changes in weather and climate. Documented trends and variability in ice dates have largely been attributed to air temperature changes (e.g. Duguay et al. 2006; Brown and Duguay 2010). Investigations of long-term trends (observable from ground-based records) and short-term (also observable from satellite data records) reveal increasingly later freeze-up and earlier break-up dates, closely corresponding to increasing air temperature trends. Broad spatial patterns in these trends and regime shifts have been associated with changes in major atmospheric circulation patterns originating from the Pacific and Atlantic oceans such as the El Niño-La Niña/Southern Oscillation, the Pacific North American pattern, the Pacific Decadal Oscillation, and the North Atlantic Oscillation/Arctic Oscillation (Bonsal et al. 2006; Prowse et al. 2011). LIC also plays an important role in weather and climate. The presence (or absence) and fractional coverage/concentration of ice cover on large lakes has a significant impact on regional weather and climate (e.g., lake-effect snowfall, thermal moderation effect).

Given the importance of ice cover in lake-atmosphere interactions, the LIC ECV will be of interest to users who wish to: (1) examine short-term trends and interannual variability in ice cover globally (ca. 20 years), (2) investigate the impact of changing ice cover conditions on other variables covered in Lakes_cci, such as Lake Surface Water Temperature (LSWT), (3) conduct data assimilation experiments using state-of-the-art numerical weather prediction systems to demonstrate the impact of better consideration of LIC on, for example, improving predictions of lake-effect snowfall and (4) evaluate lake models (e.g. FLake) used as lake parameterization schemes in numerical weather prediction and climate models. Finally, from a socio-economic perspective, the LIC variable may also serve to examine the impact of changing ice conditions on winter transportation (shipping, ice roads) and food security (access to resources by northern communities via ice roads).

3.3.2 LIC data characteristics

The LIC product consists of three variables (bands): (1) lake ice cover flag, (2) lake ice cover class and (3) the uncertainty associated with the retrieval of LIC. The lake ice cover flag indicates if ice cover was deemed possible to have formed for each grid cell. For the LIC class variable, each grid cell falling within a lake, as determined by the input lake mask, is assigned one of four possible values: water (value = 1), ice (2), cloud (3), or bad (4) in case retrieval was not possible due to poor data quality. For the uncertainty variable, grid cells take one of three possible values (expressed as a percentage): water (0.83), ice (2.23), and cloud (3.07). Uncertainty for each category has been determined globally rather than on a per-observation basis, from accuracy assessment (confusion matrix) through independent statistical validation (see End to End ECV Uncertainty Budget, E3UB, document for details).

For CDRP V2.1, the LIC product is generated on a daily basis using MODIS data acquired from multiple Terra and Aqua satellite overpasses on each day s to maximize the number of cloud-free observations. The product, which covers a 23-year period (2000-2022), is merged with the other lakes thematic products on the common (harmonized) grid described in section 4.

3.3.3 LIC data sources

The LIC product is generated from all MODIS observations available from both the Terra (since 24 February 2000) and Aqua (since 4 July 2002) satellite missions. Hence, for the period between 24 February 2000 and 3 July 2002, only Terra observations were ingested for LIC product creation.

Prior to the main processing chain, the Canadian Lake Ice Model (CLIMo) was used to determine which lakes of the Lakes_cci (total 2024 lakes) could have formed ice or have remained ice-free at any time over the 2000-2020 period. The result of this search is stored in the lake_ice_cover flag. Input data to drive CLIMo are from European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis hourly data on single levels (25 km).

The primary observation data source for lake_ice_cover class retrieval is the MODIS Terra/Aqua Level 1B Top-Of-Atmosphere (TOA) reflectance 5-min L2 swath (MOD02/MYD02), Collection 6.1 product. MODIS TOA reflectance data are used for feature retrieval (labelling as water, ice, or cloud). The TOA reflectance bands are available at 250 m (QKM) and 500 m (HKM) resolutions. The second data source for LIC product generation is the maximum water extent observed in ESA CCI Land Cover (v4.0) at 150-m resolution.

Details regarding the processing steps and the retrieval algorithm are described in the Algorithm Theoretical Basis Document (ATBD). Briefly, the processing steps consist of:

1) Load TOA reflectance (bands 1, 2, 3, 4, 5/6, 7 and SZA), geolocation (latitude and longitude), and quality raster bands from the MODIS product.
2) Identify lake (water) pixels of interest based on maximum water extent from ESA CCI Land Cover (v4.0) 150-m resolution product.
3) Identify pixel quality and label pixels of interest from application of the Random Forest algorithm for the detection of clouds, ice and open water.
4) Resample labelled pixels acquired in a day from individual swaths to the output grid at 1/120 degrees resolution and perform temporal (daily) and spatial aggregation (combining Terra and Aqua retrieved classes) in terms of each cell in the output grid.
5) Filtering the output grid to discard cells (1/120 degrees resolution) which contain land pixels using maximum water extent observed in ESA CCI Land Cover (v4.0) 150-m resolution product.
6) Writing and exporting the daily LIC product in the required format (NetCDF) with metadata.

3.3.4 LIC data limitations

The LIC daily product has been created using the longest possible MODIS time series (2000-2022) and with the intent of maximizing the number of clear-sky observations within each day. This is made feasible through the combination of multiple acquisitions from Terra and Aqua overpasses. While this approach increases the likelihood of detecting a larger number of grid cells containing ice cover or open water, the presence of cloud cover over extended periods of time across the northern hemisphere remains the greatest limiting factor for the generation of a spatially and temporally contiguous lake ice cover product from MODIS or any other optical satellite dataset.

In addition to the impact of cloud cover, users should be aware that other factors may also affect the quality of the LIC CDRP V2.1 (see E3UB document for greater details). They include, in no particular order of importance:

1) High solar zenith during fall freeze-up and early winter at high latitudes (i.e. polar darkness). For example, LIC retrieval is not possible from MODIS above ca. 85 degrees zenith at winter solstice. In such instances the data are flagged as "bad".
2) Use of the maximum water extent mask derived from ESA CCI Land Cover v4.0 at 150-m resolution product (secondary input data) to determine MODIS pixels falling within a lake. Since this mask represents maximum water extent, it can introduce some misclassification errors along the shoreline of lakes (i.e. mask spilling over land so that some MODIS land pixels may be incorrectly flagged as lake ice pixels) or for entire lakes or lake sections that dry up in summer. Other lake mask options will be examined leading to second release of the LIC product.
3) The quality and temporal continuity of the MOD02/MYD02 TOA reflectance products used as the primary input data source.
    - Although detector noise/sensor degradation and observation noise have been relatively well characterized (see E3UB document for details), there are few documented cases where noise has been found to lead to false negatives (e.g., detection of ice instead open water).
    - Regarding temporal continuity, a few years have been found not to provide data from either Terra or Aqua on some days (missing days: 12 in 2000, 17 in 2001, 19 in 2002, 7 in 2003, 2 in 2008, and 9 in 2016).
4) Reporting of uncertainty. The assessment of uncertainty in the LIC CDRP V2.1 was performed through computation of a confusion matrix built on independent statistical validation. Uncertainty was not assessed at a per-pixel level, but rather from overall classification error calculated from multiple samples/images for each of three classes (ice, water, cloud). Every pixel belonging to a class was assigned the same overall % classification error under the LIC uncertainty variable. Efforts will be placed in identifying additional metrics for consideration and possible implementation for per-pixel uncertainty assessment leading to LIC v3.0 production.

3.4 Lake Ice Thickness (LIT)

3.4.1 LIT definition and usage

Lake ice is a major landscape feature in the winter season at high latitudes and plays a key role in climate moderation and the energy balance (Brown and Duguay 2010). Lake ice conditions, particularly the length of the ice season and ice thickness, have a significant impact on the economy, particularly in northern regions through their influence on transportation, travel, fishing, and recreation (Ghiasi et al. 2020). Therefore, accurate knowledge about lake ice properties, such as lake ice thickness (LIT), is necessary. Furthermore, LIT integrates changes in surface air temperature and on-ice snow mass (depth and density) (Brown and Duguay 2010) and is, therefore, a good proxy of winter severity.

3.4.2 LIT data characteristics

The LIT product consists of LIT time series with the associated uncertainty. These are estimated by performing a retracking analysis of radar altimetry waveform data as described in Mangilli et al. (2022), and further detail is also provided in the ATBD and E3UB.

A quality flag is included in the product with the following values: 0 for good data, 1 for bad or missing data and 2 for poor data, in case the average waveform fit performance in the region of interest is degraded. In general, LIT data with quality flag 2 are not frequent and typically localized at the seasonal transitions. These data can be used, noting lower LIT retrieval performance and increased uncertainty.

The LIT product delivered for CRDP v2.1 consists of three LIT time series generated from three different regions of interest (RoI) over the Great Slave Lake (Canada). The LIT time series are computed from December 2001 to April 2022 with a temporal resolution 10 days, corresponding to a data cycle (that is, the time of revisit of the same ground pass) of the radar altimetry satellites used to generate the LIT estimations. Given that, for this first release, the LIT data are generated only for a single lake, the LIT product is kept in a separate file with respect to the other ECVs. The CRDP v2.1 LIT product represents the first long LIT time series (> 20 years) over Great Slave Lake, allowing lake ice climatological studies over this target.

3.4.3 LIT data sources

The data used to generate the LIT time series product are Low Resolution Mode (LRM) Ku-band radar altimetry waveform data at 20 Hz from Jason-1, Jason-2 and Jason-3 missions over Great Slave Lake (GSL). The satellites are on the same orbit, so they cover the same area of GSL, allowing for consistent LIT estimations over time. The LIT time series have been generated from three different Regions of Interest (ROI) of the lake, corresponding to three along-track segments of the three satellite overpasses (pass 45, 178 and 254 respectively). Each of the RoI along-track segment used for the LIT analysis spans ~0.1° in latitude, including more than one hundred radar waveforms, within a distance of $\simeq$ 35 km along the altimeter track. The location of each RoI has been chosen to be far enough from the lakeshore, so that the radar echoes are not contaminated by spurious signals from land, while the length of the segment has been chosen to provide enough statistics for the LIT estimation while limiting the spatial coverage and, thus, the spatial evolution of LIT within the segment in order to obtain consistent constraints within the RoI, in particular at the seasonal transitions. The LIT time series product has been generated by analysing the radar waveform data with the LIT retracker described in Mangilli et al. (2022).

3.4.4 LIT data limitations

A few limitations of the LIT product have been identified, mainly related to LIT estimations at the seasonal transitions:

1. The LIT retracker faces challenges in precisely estimating ice thickness in the initial days of ice formation and once melt begins. This issue has been reported in Mangilli et al. (2022).
2. In the absence or minimal presence of snow on the ice surface, the step-like feature required to estimate LIT from the analytical approach (Mangilli et al. 2022) does not appear in the radar waveforms, leading to underestimated LIT retrievals.
3. The presence of leads or footprints with mixed open water and ice results in poor estimation of LIT values.

The LIT retracker (Mangilli et al. 2022) can capture the seasonal transitions of ice forming and melting but cannot precisely follow the ice evolution at the transitions because of the difficulty of retracking heterogeneous surfaces when the ice is too thin and when snow on the ice surface begins to melt.

3.5 Lake Surface Water Temperature (LSWT)

3.5.1 LSWT definition and usage

LSWT is the surface expression of the thermal structure of lakes which is changing in response to climatic trends. LSWT is needed for climate change studies, water budget analysis (linked to evaporation), lake physical and ecological modelling.

Lake surface water temperature (LSWT) is the temperature of the upper layer of lake water. In the case of a satellite observation of LSWT, the obtained value is sensitive to the skin temperature of the water, which is the temperature of a layer <0.1 mm thick from which thermal radiation is emitted by the lake. In Lakes_cci products, the LSWT is an estimate of this skin temperature, which may differ from the temperature as measured by a thermometer a few centimetres below the water-air interface. Typically, the temperature difference between skin and sub-skin LSWT is of order –0.2 K (meaning, the skin temperature is on average cooler). However, the difference depends on meteorological conditions. Although the skin effect is variable, the satellite LSWT is nonetheless tightly coupled to the LSWT as measured conventionally, and satellite LSWT has been used to quantify worldwide aspects of lake thermal dynamics such as seasonal cycles (Maberly et al. 2020), onset of summer stratification (Woolway and Merchant 2018), lake mixing dynamics (Woolway and Merchant 2019), over-turning behaviour (Fichot et al. 2019) and several other aspects of lake-climate interactions.

3.5.2 LSWT data characteristics

Users of the Lakes products will note that the LSWT fields are not, in general, spatially complete. This is because the LSWT estimation process (MacCallum and Merchant 2012) is valid only for cloud-free views of the water surface from space, since the satellite sensors rely on infrared wavebands to which clouds are opaque. The degree of unobserved surface is therefore variable in time and space, according to weather conditions. In regions with persistent cloud cover observations may be rare.

The primary LSWT variable is the lake surface water temperature field itself. Two other LSWT variables should, however, be considered by users: (1) an estimate of uncertainty is provided per datum. The provided uncertainty field is an evaluation of total standard uncertainty (so-called "1-sigma"), and is estimated within the LSWT retrieval process. The uncertainty arises from a range of sources, some of which are independent between data, while other sources cause errors that are correlated to other nearby data. (2) A quality level is provided per datum. This is an index ranging from 2 (suspect/marginal quality) to 5 (best quality). "Quality" here means the level of confidence that the LSWT value and its evaluated uncertainty are both valid (Merchant et al. 2017). For climate applications, we recommend use of quality levels 4 and 5. However, LSWT with quality levels 2 and 3 are present in the product, and users can assess their usefulness for their own application. Quality levels 1 (bad) and 0 (unprocessed) are never valid and their use should be avoided.

The provided data are on the same regular latitude-longitude grid as the other Lakes ECV products, which means they have been regridded from the less regular pixel locations originally observed by the satellite sensors.

3.5.3 LSWT data sources

As background information, the basis on which LSWT data are obtained is summarised in this section. For full details of the basis of the data, refer to the Algorithm Theoretical Basis Document.

The algorithms to derive LSWT products aim to retrieve the LSWT from the observed reflectance and brightness temperature for only inland water pixels. The core retrieval is the Optimal Estimation (OE) of LSWT, which is a form of Bayesian inference of the LSWT given the difference between the satellite observations and simulations of those observations made for an assumed LSWT (the prior value). The other components of the algorithm prepare the inputs for the retrieval, classifying a satellite pixel as water or non-water. Finally, the observations are gridded and a cross-sensor adjustment is estimated and applied in order to obtained a harmonized result across the several sensors that contribute.

Preparatory processing: this includes orbit file reading, validity checks, association of auxiliary information to the orbit file being processed (including prior fields from numerical weather prediction, where relevant), and any pre-processing adjustment to the data themselves.

Classification: this step identifies valid pixels for LSWT retrieval. Although sometimes referred to as cloud detection, this also involves identifying which image pixels cover only lake water (no coast or islands within the pixel), and exclusion of pixels affected by ice (for which LSWT cannot be obtained). Valid LSWT is estimated only for pixels that are fully water and free of cloud. The algorithm for the discrimination of water and non-water pixels in presence of clouds is based on threshold tests on the visible, near-infrared, and short-wave-infrared channels of the ATSR and AVHRR instruments. The water detection algorithm is applied only to candidate pixels identified as potential inland water in the water-bodies identifier mask (Carrea et al. 2015) built from the ESA CCI Land Cover project.

Retrieval of LSWT (geophysical inversion): for pixels classified as water, LSWT is calculated dynamically given prior information with the Optimal Estimation technique (MacCallum and Merchant 2012). The prior information comprises NWP fields as inputs to a radiative transfer model, whose simulations in comparison to the observations are used in the retrieval. The LSWT is estimated for each (clear-sky) water pixel using joint optimal estimation of surface temperature and Total Column Water Vapour given the simulations and observations. The form of OE used is to return the Maximum A-posteriori Probability assuming Gaussian error characteristics. OE also gives an uncertainty estimate for each retrieval. Quality levels are also estimated which reflects the degree of confidence in the validity of the uncertainty estimate (not the magnitude of data uncertainty).

Gridding/averaging: the algorithm grids the irregular swath-based imagery into the regular grid.

Daily collation: the complete 14-15 orbits each day per sensor are collated to produce one data layer for each 24-hour period, corresponding to day-time observations. The average of the best quality observations from all available sensors is used as the combined gridded LSWT for each grid cell.

Inter-sensor adjustment: to stabilise the record for changes in satellite sensor, an adjustment using overlaps of sensors is made, using as the (unadjusted) reference the LSWTs from the AVHRR on MetOpA.

3.5.4 LSWT data limitations

The classification algorithm relies on threshold tests, using one generic set of thresholds for all the lakes (although some in reality have different reflectivity). For any classification scheme, some water pixels may have not been detected as water and some non-water pixels may have been included in the set of pixel where the retrieval has been applied. The classification scheme is “fuzzy”: the confidence of the water detection is captured in a water detection score which is used (together with other parameters) to set the value of the LSWT quality levels.

The emissivity assumed in the LSWT retrieval is always set to that of fresh water, and for highly saline lakes, this may introduce some small bias (whose magnitude is yet to be assessed, and may be negligible). The retrieved LSWT corresponds to the skin temperature of the lake (the radiating layer of surface water), and a cool offset of order 0.2 K should be expected relative to sub-surface water temperature measurements.

The temporal density of observations of any particular quality varies greatly between lakes. Lakes that are narrow (only a couple of kilometres across) generally produce few water-only pixels with these sensors (whose best resolution is 1 km), even if the lake is extensive and its area overall is large. Some lakes that are targeted in the products, but whose geometry is unfavourable, may have few or no high quality LSWT results.

Prior to the availability of global 1-km resolution MODIS (Terra) observations (2000 onwards), the temporal density of observations is generally lower because of the lesser coverage from the earlier ATSR series instruments used. After 2006, the data density increases further because of the availability of AVHRR (MetOpA) observations.

3.6 Lake Water Leaving Reflectance (LWLR)

3.6.1 LWLR definition and usage

Lake Water-Leaving Reflectance (LWLR), also referred to as water colour, is the quantity of sunlight reaching the remote detector after interaction with the water column. The maximum depth from which the reflected signal is observed depends on the optical properties of the water column, is dependent on the colour band (waveband) considered and, in natural waters, can range from tens of meters (up to nearly 100 m in the clearest ocean waters) to just centimetres in highly absorbing and/or turbid waters. The colour of water is retrieved using imaging or line-scanning optical detectors on satellites. Each sensor offers a specific trade-off between the observation time (longer periods yielding lower instrument noise) and the spatial resolution as well as the number of discrete wavebands in which reflectance is measured. Because relatively small changes in absorption by, for example, phytoplankton pigment need to be distinguishable, an adequate signal-to-noise of an ocean-colour sensor for the signal received at the top of the atmosphere should be at least 1000:1 (IOCCG 2012). Correspondingly, the spatial footprint of such sensitive detectors on modern polar-orbiting satellites which scan the entire Earth every 2-3 days (a speed-over-ground exceeding 25,000 km/h) is around 300m at the equator. For previous sensors with less advanced detectors, which may also have been limited by downlink capacity, the spatial resolution tends to be 1 km or coarser while the number of discrete wavebands has increased from eight (at 10 bits digitization) on SeaWIFs (1997-2010) to 21 (using 12-bit precision) on OLCI (2016-present).

Lake Water-Leaving Reflectance (LWLR) is the result of atmospheric correction of top-of-atmosphere radiance over water pixels. This correction is the result of model optimization and subject to the possibility of ambiguous solutions. The main effects that introduce uncertainty are mixing of reflectance from water and nearby land in the atmosphere, bottom reflectance, in-water bio optical model ambiguities and limited waveband configurations to help bound the mentioned numerical optimisation.

Once LWLR is estimated, several optical-biogeochemical characteristics of the lake may be determined from its colour. The main quantities of interest are:

- The concentration of phytoplankton pigment, particularly chlorophyll-*a*, which is found in all species as the major photosynthetic pigment.
- Vertical transparency, for submerged vegetation habitat mapping or primary production models when combined with chlorophyll-a and temperature observations or models
- The concentration of (coloured) dissolved (organic) matter as a proxy for the dissolved organic Carbon pool, as well as the quality of underwater light.
- The total amount of suspended sediment (TSM), either expressed as equivalent particulate dry weight or as the Turbidity caused by it.

Currently, globally validated algorithms to retrieve such quantities are available for chlorophyll-*a* and TSM or Turbidity, and vertical transparency, with by far most of the attention in scientific literature dedicated to the retrieval of chlorophyll-*a.*

3.6.2 LWLR data characteristics

The daily observations used for CDRP v2.1 are obtained from the Envisat-MERIS (2002-2012), Aqua-MODIS (2002 – present) and Sentinel-3 OLCI (2016 – present) satellite sensors. They are provided on a common grid with the other Lakes Essential Climate Variables. MERIS and OLCI sensors offer a native 300 m resolution, whilst for MERIS the 1km reduced resolution data provides better spatio-temporal coverage. MODIS observations are obtained at 1 km resolution and only used to fill the gap between MERIS and OLCI (April 2012-April 2016) in lakes were reasonable consistency with the other sensors is observed. The use of MODIS is typically limited to large lakes, as correcting for atmospheric effects including those exacerbated by nearby land is more difficult due to the absence of key wavebands usef in the correction, in the near infrared. MERIS and OLCI also offer better retrieval capabilities for chlorophyll-*a* in relatively turbid water, through a 709 nm waveband in the near infrared.

Data are not be available for each of the included lakes at every datum. This is due to a combination of satellite overpass limitations (more frequent with OLCI than with MERIS, particularly for 2019-present when two OLCI sensors were in simultaneous operation) and removal of pixels affected by cloud (including edges and shadows) or ice.

The LWLR is presented in a number of discrete wavebands corresponding to the frequency or wavelength of light across the visible to near infra-red spectrum. The number of wavebands differs per sensor and each sensor has variations in where the bands are centred. No attempts have been made to 'shift' the signal of any sensor to match that of others, because the underlying reflectance form is neither known nor modelled, owing to the wide optical variability of inland water bodies (compared to oceans for example). However, bands that are within 6 nm of an OLCI waveband are presented as belonging to the same position along the spectrum. This has been done to reduce the number of variables in the dataset, and to allow easier ingestion and analysis of time-series data. For details on the waveband definitions of the individual sensors, please refer to the ATBD, and refer to the metadata of each data file to see which sensor was used for a particular datum.

In addition to LWLR the CDRP V2.1 includes estimates of chlorophyll-*a* (mg m^{-3}) and turbidity (NTU) which are derived from the LWLR. For a detailed overview of the algorithms and correction used to obtain these estimates please refer to the ATBD. Each product also comes with an associated per-pixel product uncertainty estimate, as long as sufficient in situ reference observations were available to model the uncertainty for the specific variable, observed value range and lake optical type. The procedure used to determine product uncertainties is defined in the E3UB document.

3.6.3 LWLR data sources

The full observation archive from Envisat-MERIS and Sentinel-3 OLCI-A/B is used to assess the full set of Lakes_cci targets (2024 in total). These archives contain observations from April 2002 until April 2012 for MERIS and April 2016 – present for OLCI. CRDP v2.1 includes all years up to 2022. MERIS satellite passes identified as invalid were omitted. The MERIS data are the L1B Reduced Resolution from the 3rd reprocessing by ESA, selected because this has wider spatiotemporal coverage than the Full Resolution archive. The OLCI source data are L1B at full resolution. From v2.0 of the CRDP onwards, Aqua-MODIS data are processed and included in the dataset to fill the gap between April 2012 and April 2016. These data are only included where MODIS-Aqua time-series are consistent with MERIS and OLCI-A/B during a period of overlapping observations of three-years before and after the gap.

The observed area per lake is defined by the maximum water extent following the ESA Land Cover CCI v4.0 water mask. Within this water extent, land/water/ice/cloud classification is performed. Areas outside the maximum water extent are not considered here.

3.6.4 LWLR data limitations

The LWLR data set is provided for every pixel recognised as water from the optical observations. However, at the spatial resolution of the satellite sensor (nominally 300-1km) there is a risk of 'mixed pixels': water in which small fractions of land, cloud, ice or vegetation are included. The water classification is set up to be restrictive: when classified as water, other influences are likely to be minor. However, given the difference in optical contrast between water and other features even minor differences can lead to large estimation errors, which are then most likely to be found near land (and islands), cloud fringes and floating or shoreline vegetation. Users are advised to consider their application of the data with care, and e.g. consider removing data near shorelines to answer questions about long-term change.

Mixed-pixel effects are also observed during periods of freeze-up and ice melting, when thin or partial ice cover may not be efficiently recognised. From v2.1 onwards, outlier values that are associated with (partial) ice cover, observed during periods of low water temperature, are flagged as 'lwlr_poor_consistency' or 'lwl_low_consistency' respectively when either all or some of the observations within a pixel were affected.

The major source of uncertainty in lake optical water quality estimation is the separation of water-leaving radiance from atmospheric effects. The latter increase in severity nearby land and this 'adjacency effect' can, depending on the state of the atmosphere, extend several kilometres. This has two major influences on the observations:

- Longer wavebands tend to be more affected by mixing of reflectance from land and water, because the contrast in reflectance from these features is largest in these wavebands. This affects particularly the retrieval of turbidity (which relies on near-infrared reflectance) and chlorophyll-a at concentrations > 10 mg m^{-3} (which uses red and near-infrared wavebands).
- Elevated near-infrared reflectance introduced from nearby land may lead to over-correction of LWLR at shorter wavebands.

The shape of the LWLR spectrum has been analysed to identify likely influence of nearby land. When this is detected, a quality flag (lwlr_land_contaminated) is raised, to be used at the discretion of the data user. Particularly in small lakes this flag may be raised for a considerable fraction of observations, depending on the thickness of the atmosphere.

Overall, validation results to date suggest that atmospheric correction procedure yields a systematic under-estimation of LWLR. This effect has not been corrected for because the validation itself is uncertain due to limited availability of in situ reference data. It is anticipated that this affects the retrieval of lake colour intensity more than lake hue. Chlorophyll-a and turbidity estimates are not equally affected by this issue, because their retrieval is calibrated directly against in situ reference measurements.

Per-pixel uncertainty estimates for chlorophyll-a and turbidity are currently modelled as a function of algorithm performance per optical water type (see the E3UB document for details). Other effects such as proximity to land have not been included in this model, but will likely explain a significant fraction of the overall product uncertainty. This implies that the uncertainties in open water are likely to be a worst-case estimate at present.

Given the perceived systematic negative bias in LWLR, per-pixel uncertainty estimates for each LWRL waveband for which in situ data are available, are provided both as the relative difference (which includes the negative bias) and the un-biased relative difference. The latter provides a better estimate of the effect of other sources of uncertainty in LWLR on downstream biogeochemical retrieval algorithms, as these are individually calibrated against in situ reference measurements.

4 Lakes ECV Dataset

4.1 Definition

The Climate Research Data Package (CRDP) intended to fulfil the Lakes ECV observation challenge is a merged ('L3S') product composed of the thematic products described in the previous sections:

- Lake water level (LWL)
- Lake water extent (LWE)
- Lake Ice Cover (LIC)
- Lake Surface Water Temperature (LSWT)
- Lake Water Leaving Reflectance (LWLR)

The Lake Ice Thickness product is provided in separate files. In this version, the LIT product is only available for Great Slave Lake (Canada) for three different satellite tracks.

The global coverage of CRDP v2.1 is shown in Figure 1. A list of lakes including their location and thematic ECV data availability, can be found on the project website in comma-separated text format.

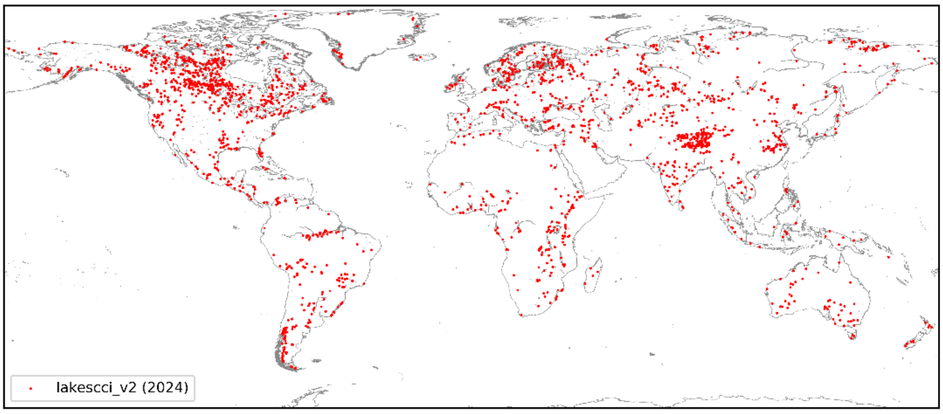

Figure 1: Inland waterbodies included in CRDP v2.1

4.2 Main characteristics

Data generated in the Lakes_cci project are derived from multiple sensors and satellites (for details see the Product Specification Document (PSD)) and, consequently, different temporal and spatial resolutions. One of the objectives in Lakes_cci project is the harmonisation of the different products as a single dataset with the following characteristics:

- Daily aggregation interval (products are specified as 12:00:00 UTC).
- Grid format with spatial resolution of 1/120 degrees (near 1 km at the equator).
- Variables not produced in grid format (LWL and LWE) are duplicated in the grid for the area given under the nominal spatial delineation of that lake.
- Common 1/120 degree grid (latitude and longitude)
- Common regions of interest. The full set of lake definitions is made available as a set of polygons and on the global grid equivalent to the CRDP. The definitions are based on the maximum water extent V4.0 maps from ESA Land Cover. The grid representation of the lake definitions also contains the distance to the nearest land for each lake pixel.
- Extent: -180 to 180 degrees longitude, -90 to 90 degrees latitude, where positive signs point north and east. The pixel coordinate is the centre of the pixel.

Uncertainty estimates are provided for each product. Procedures to derive uncertainty estimates are provided in the End-to-End Uncertainty Budgets document (E3UB).

The sequential identifiers of the lake regions follow the Global Lakes and Wetlands Database and Hydrolakes databases, respectively. Where these databases overlap or where their delineations of water bodies is incomplete, the numbering follows the provenance of projects where they were initially defined (Table 4), so that users can combine old and new datasets.

Table 4 Provenance of lake identifiers

ID	Provenance
000000000 – 099999999	Global Lakes and Wetlands Database
100000000 – 199999999	GloboLakes project
200000000 – 299999999	Copernicus Land Monitoring Service
300000000 – 399999999	Hydrolakes

4.3 Nomenclature

File naming in the Lakes_cci follows the CCI standard formatting:

ESACCI-LAKES-<Processing Level>-<Data Type>-<Product String>-<Indicative Date>-fv<Version>.nc

Where:

Processing Level: L3S, meaning reprojected and super-collated. Observations from multiple instruments and observation times are combined into a common spatiotemporal grid.

Data type: LK_PRODUCTS

Product String: MERGED, meaning data combined from more than one platform / sensor.

Indicative Date: YYYYMMDD format, the date of the observations.

Version: 2.1.0

Thus, an example file name in the first data release is:

ESACCI-LAKES-L3S-LK_PRODUCTS-MERGED-20190214-fv2.1.0.nc

For LIT products, delivered in three separated files, the nomenclature is as follow:

ESACCI-LAKES-L3S-LK_PRODUCTS-LIT-GreatSlave-Pass<Pass number>.nc

Where Pass number can be 45, 178 or 254, the pass number of the missions monitoring Great Slave Lake.

4.4 Format

The Lakes_cci dataset is stored in the NetCDF 4 classic format (Network Command Data Form) using the CF (Climate and Forecast) metadata convention (v1.8) and CCI Data Standards (v2.3).

The following sections describe the components of each NetCDF for the merged product and for the LIT files.

4.4.1 Merged product

4.4.1.1 Global attributes

The global attributes provide general information about the product. The Lakes_cci global attributes are those recommended in the CF standards (Table 5)

Table 5. CF Global Attributes

Attribute Name	Attribute description
title	description of the dataset
institution	where the data were produced
source	original data source
history	processing history of the dataset
references	reference website

Additionally, the NetCDF files contain the recommended global attributes for dataset discovery and additional attributes defined in the CCI data standards v2.3 (Table 6).

Table 6. CCI Global Attributes

Attribute Name	Attribute description
tracking_id	Universal Unique Identifier (randomly generated)
conventions	CF and CCI Data Standards
product_version	Lakes_cci merged product version
summary	description of the dataset
keywords	list of keywords
keywords_vocabulary	science keywords
id	filename
naming authority	lakes.esa-cci
cdm_data_type	Grid
date_created	Date of file creation
creator_name	ESA Lakes_cci
creator_url	http://cci.esa.int/lakes
creator_email	lakes_cci@groupcls.com
project	Climate Change Initiative - European Space Agency
geospatial_lat_min	-90.0
geospatial_lat_max	90.0
geospatial_lon_min	-180.0
geospatial_lon_max	180.0
geospatial_vertical_min	NA
geospatial_vertical_max	NA
time_coverage_start	Start of observations in ISO8601 format
time_coverage_end	End of observations in ISO8601 format
time_coverage_duration	File time coverage duration in ISO8601 format

Attribute Name	Attribute description
standard_name_vocabulary	NetCDF Climate and Forecast (CF) Metadata Convention
License	ESA CCI Data Policy: free and open access
Platform	list of satellites used in this data file
Sensor	list of sensors used in this data file
spatial_resolution	1 km at Equator
key_variables	water_surface_height_above_reference_datum, lake_surface_water_extent, lake_ice_cover_class, lake_surface_water_temperature, chla_mean, turbidity_mean, Rw[xxx] where xxx is one of 400, 412, 443, 469, 490, 510, 531, 547, 560, 620, 645, 665, 674, 681, 709, 754, 779, 859, 885, 900, 1020nm
geospatial_lat_units	degrees north
geospatial_lon_units	degrees east
geospatial_lat_resolution	0.0083333
geospatial_lon_resolution	0.0083333
doi	Digital Object Identifier of the dataset

Appendix A -contains an example of these global attributes.

4.4.1.2 Dimensions

Following the CCI data standards, the gridded products of the Lakes_cci have three dimensions: time, latitude and longitude. As indicated in chapter 4.2, for reasons of consistency, all the included variables share the same dimensions.

4.4.1.3 Variables

The attributes of the variables in the NetCDF files follow the CCI data standards guidelines and consequently, the CF recommendations:

- standard_name: standard name if it exists in the CF convention
- long_name: description of the variable in human-readable format
- units: units of the variable
- valid_min: smallest value to be considered valid
- valid_max: largest value to be considered valid
- _FillValue: the value used to indicate lack of data
- scale_factor (optional): multiplicative factor for packing data
- add_offset (optional): additive offset for packing data
- comment (optional): Miscellaneous information for the user, such as the meaning of product quality flags
- grid mapping
- ancillary_variables: indicated in the primary variable
- flag_values and flag meanings: defined for flag variables

The variables included in the dataset are listed in Table 7

Table 7. List of variables in the NetCDF file

Variable Name	Lakes_cci product
water_surface_height_above_reference_datum	LWL
lwl_uncertainty	LWL
lwl_quality_flag	LWL
lake_surface_water_extent	LWE
lwe_uncertainty	LWE
lwe_quality_flag	LWE
Lake_ice_cover_flag	LIC
lake_ice_cover_class	LIC
lake_ice_cover_uncertainty	LIC
lake_surface_water_temperature	LSWT
lswt_uncertainty	LSWT
lswt_quality_level	LSWT
Rw[xxx]*	LWLR
Rw[xxx]_uncertainty_relative*	LWLR
Rw[xxx]_uncertainty_relative_unbiased*	LWLR
lwlr_quality_flag	LWLR
chla_mean	LWLR
chla_uncertainty	LWLR
turbidity_mean	LWLR
turbidity_uncertainty	LWLR

* where xxx is one 400, 412, 443, 469, 490, 510, 531, 547, 560, 620, 645, 665, 674, 681, 709, 754, 779, 859, 885, 900, 1020nm.

4.4.1.4 Data availability

As described in section 1.2, data used for the generation of the lakes_cci product come from multiple instruments in different missions. Thus, the temporal resolution and spatial coverage are not the same for all variables. Figure 2 to Figure 4 show the spatial coverage of the data for LWL, LWE and LSWT respectively. Temporal time step for LWL and LWE is satellite dependant, ranging from daily for lakes observed by multiple missions/tracks to 27 days for lakes being observed by sentinel-3A/B missions. LIC data is available since 2001 for all lakes with a flag indicating whether a lake do not form ice. LWLR data is available for all lakes since 2002. Among them, 48 lakes have complete datasets spanning from 2002 to 2022, while the remaining lakes have a gap in data between 2012 and 2016. The data availability is classified in five categories:

- Lakes with data available at least 50% percent of the temporal coverage (16 years) – dark green dots
- Lakes with data available less than 50% of the temporal coverage – light green dots
- Lakes no covered by satellite instruments – black dots
- Lakes analysed with rejected data because the low quality of the measurements – red dots
- Lakes still under analysis – orange dots

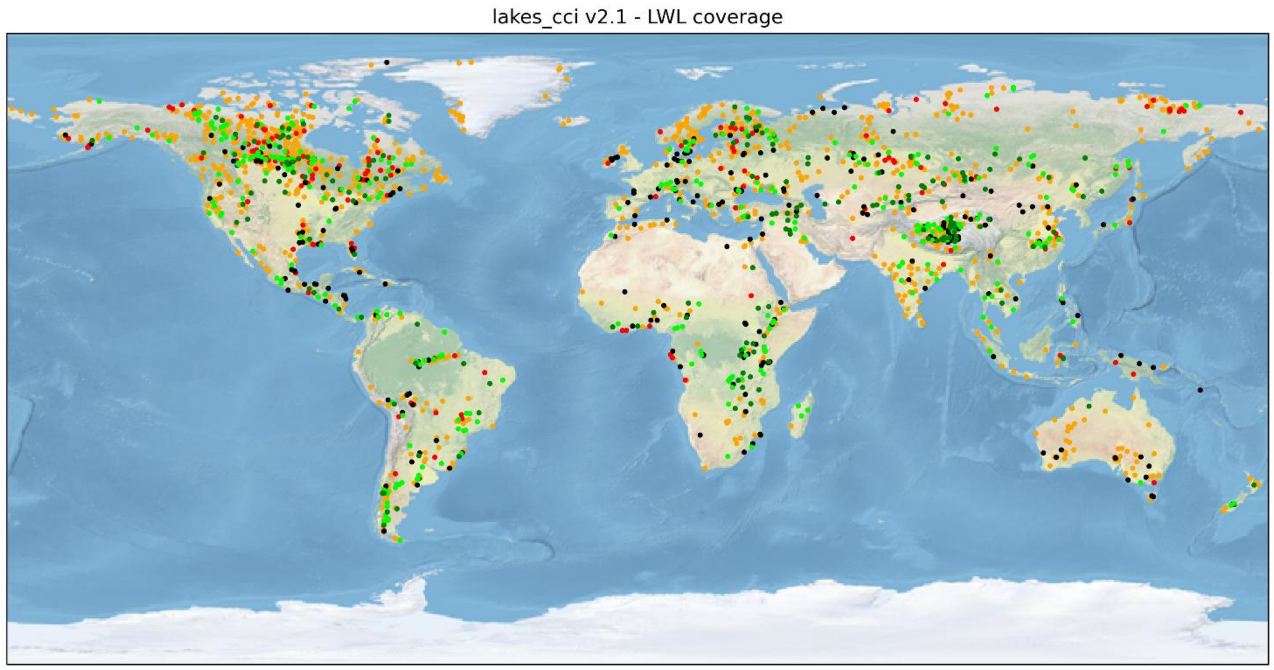

Figure 2. Lake Water Level spatial coverage (starting in 1992)

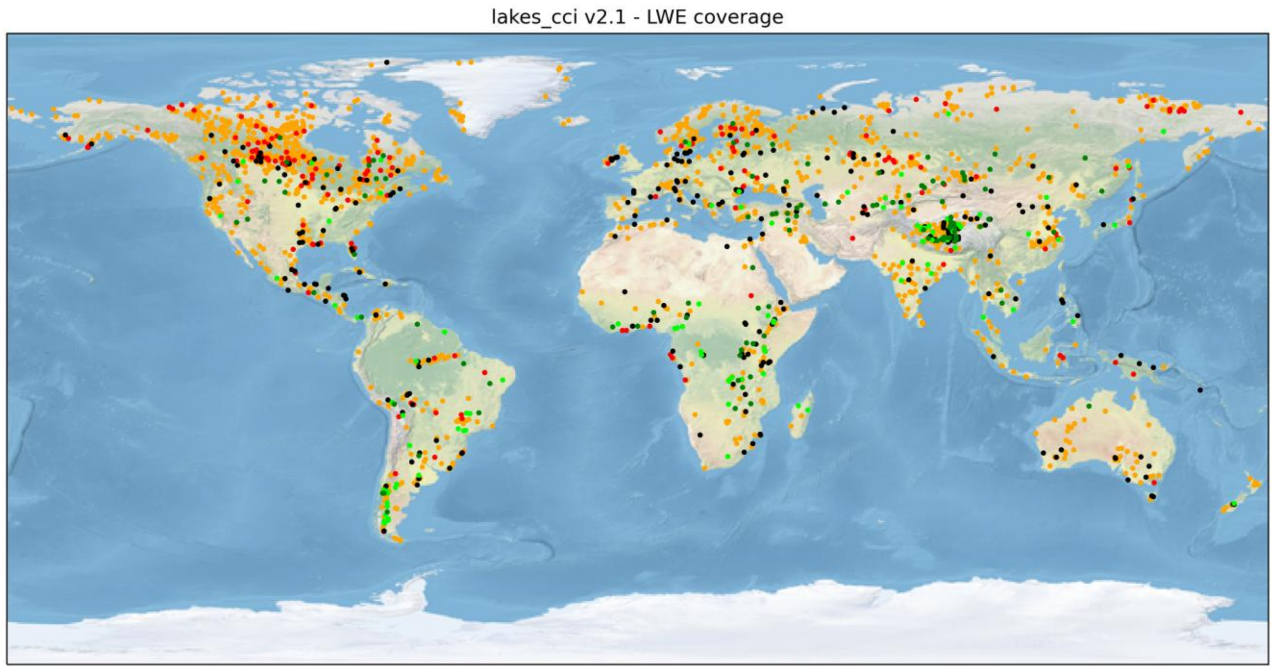

Figure 3. Lake Water Extent- Spatial coverage (starting in 1992)

lakes_cci v2.1 - LSWT coverage

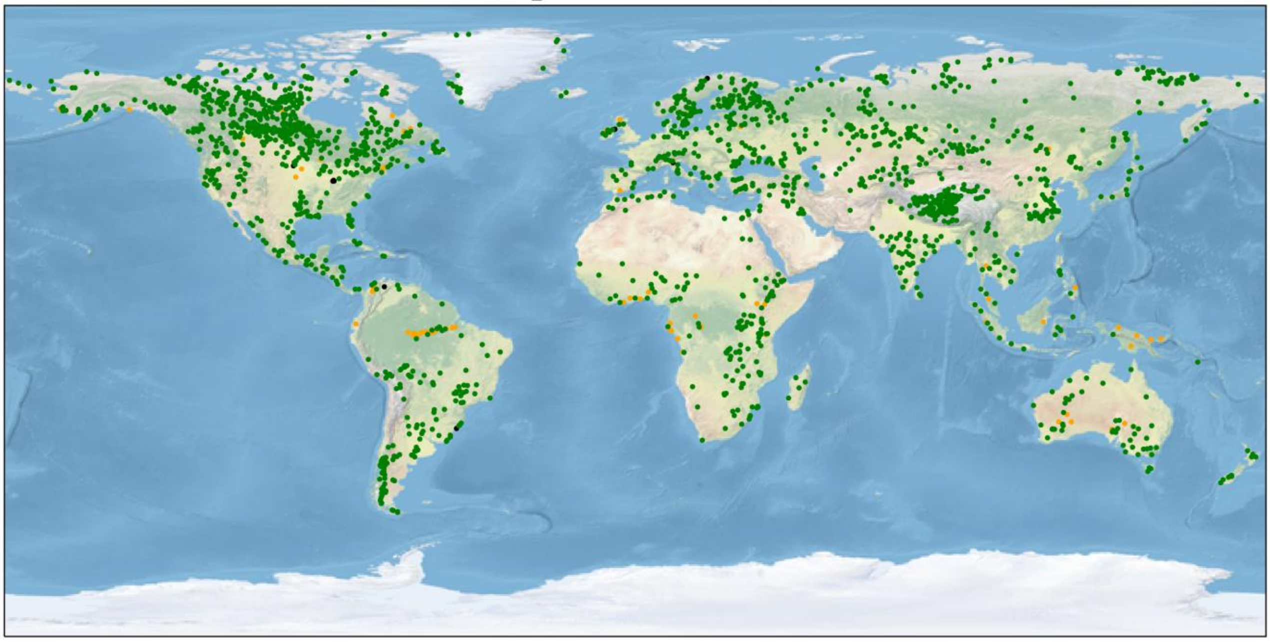

Figure 4. Lake Surface Water Temperature – Spatial coverage (starting in 1995)

4.4.2 LIT Product

4.4.2.1 Global attributes

As for the merged products, the LIT files contain global attributes recommended in the CF standards (Table 8) as well as those recommended by CCI data standards (DataStandards_v2.3)

Table 8. LIT CF Global Attributes

Attribute Name	Attribute description
title	description of the dataset
institution	where the data were produced
source	original data source
history	processing history of the dataset
references	reference website
summary	description of the dataset
keywords	list of keywords
id	filename.nc
naming_authority	lakes.esa-cci
comment	These data were produced for the ESA Lakes_cci project
creator_name	ESA Lakes_cci
creator_email	lakes_cci@groupcls.com
project	Climate Change Initiative - European Space Agency
standard_name_vocabulary	NetCDF Climate and Forecast (CF) Metadata Convention
license	ESA CCI Data Policy: free and open access
platform	Jason1, Jason2, Jason3

Attribute Name	Attribute description
key_variables	LIT
latitude	latitude of the center of the LIT ROI:
longitude	longitude of the center of the LIT ROI
time_coverage_start	First time available in the file in ISO8601 format
time_coverage_end	Last time available in the file in ISO8601 format
doi	Digital Object Identifier of the dataset

4.4.2.2 Dimensions

The only dimension for LIT products is time. Each file contains measurements for a complete time series.

4.4.2.3 Variables

There are three variables in the LIT files:

- Lit: Lake Ice Thickness
- Lit_uncertainty expressed in meters.
- Lit_quality_flag: good, bad_no_data, degraded_fit_performance

For the first two variables, the units and valid range are in the variable attributes. For the quality_flag variable, the values and the meaning of the flags are indicated as indicated in the CF recommendations.

5 Supporting software

Lakes_cci data are stored in the NetCDF4 classic file format. A wide choice of software packages can be used to visualise or manipulate the NetCDF data. A list of software is provided on the Unidata web site[1].

There are several ways in which you can explore, download, and analyse the Lakes_cci datasets.

- The data are hosted at CEDA, where you find the full global datasets as well as the lake mask with the maximum extent. CEDA offers multiple download mechanisms and ways to extract a set of variables, or data for a specific region.
- To explore some of the ways in which you can extract data for a specific lake or region, we offer a series of python scripts and a jupyter notebook. These are intended to help new users familiarise themselves with data extraction for further analysis: https://github.com/cci-lakes/lakes_cci_tools
- For interactive visualisation of the dataset you can use the WebGIS. The light-weight GIS provides visualisation of most variables (Figure 5), and has functionality to extract small sections of the data for download or plotting (for larger requests, please use the CEDA tools). This is also a useful resource for training and education, e.g. by sharing links to your visualisation with others: https://lakescci.eofrom.space

[1] https://www.unidata.ucar.edu/software/netcdf/software.html

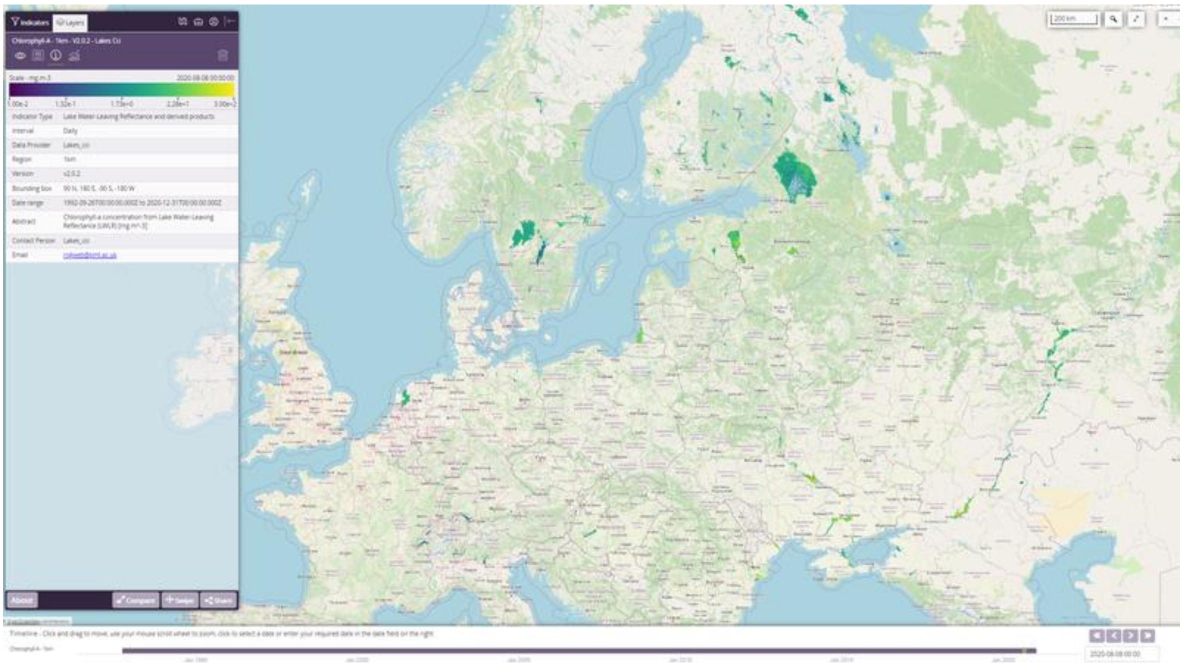

Figure 5. Lakes_cci light-weight GIS

The Lakes_cci Global Climate Indicators Dashboard (Figure 6) provides intuitive visualization of change in lakes using a range of aggregation methods (e.g. country, continent, altitude, population pressure). Current indicators include the Lake Surface Water Temperature anomaly, lake heat wave occurrences and change in ice-covered area. The dashboard is hosted at https://lakescci.climate-indicators.brockmann-consult.de and will be extended with additional indicators and functionalities. Anyone interested in additional climate indicators is welcome to contact the developers at info@brockmann-consult.de

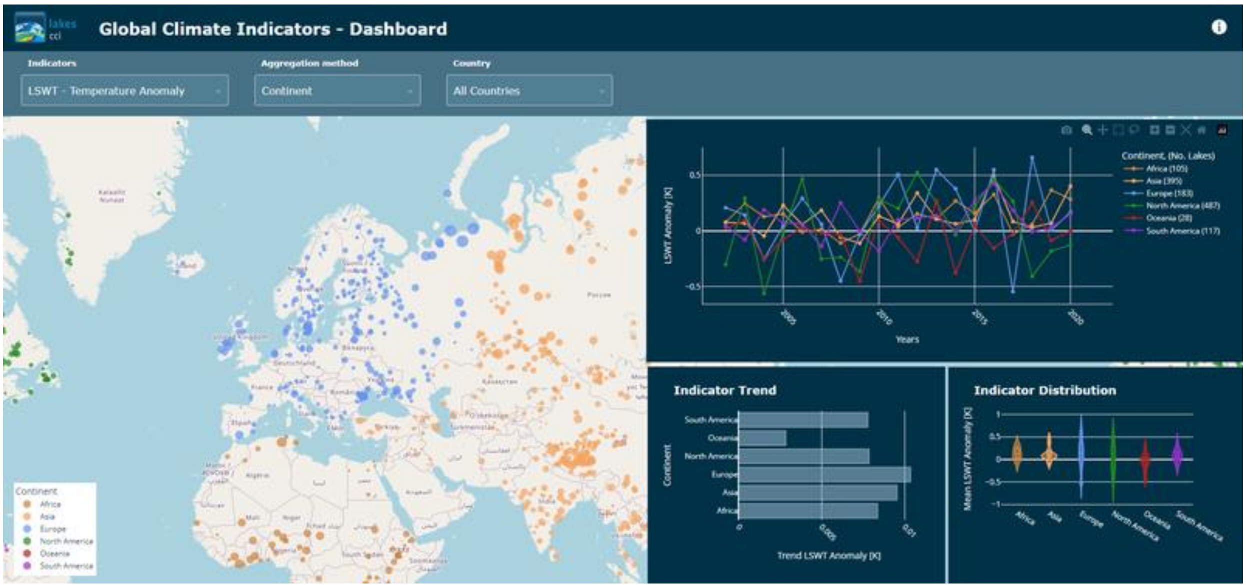

Figure 6. Lakes_cci Global Climate Indicators Dashboard

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Appendix A - Example of Global attributes for merged files

Attribute	Value
title	ESA Lakes_cci product
institution	LWL: Laboratoire d'Etudes en Geodesie et Oceanographie Spatiales, Collecte Localisation Satellites;
	LWE: Laboratoire d'Etudes en Geodesie et Oceanographie Spatiales, Collecte Localisation Satellites
	LSWT: University of Reading
	LIC: H2O Geomatics
	LWLR: Plymouth Marine Laboratory
source	LWL: European Space Agency (ESA), National Aeronautics and Space Administration (NASA), European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), National Oceanic and Atmospheric Administration (NOAA), Indian Space Research Organisation (ISRO)
	LWE: European Space Agency (ESA), National Aeronautics and Space Administration (NASA)
	LSWT: European Space Agency (ESA), European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), European Centre for Medium-Range Weather Forecasts (ECMWF), National Aeronautics and Space Administration (NASA)
	LIC: European Space Agency (ESA), National Aeronautics and Space Administration (NASA)
	LWLR: European Space Agency (ESA), National Aeronautics and Space Administration (NASA)
history processing history of the dataset	LWL: Generated by Laboratoire d'Etudes en Geodesie et Oceanographie Spatiales, Collecte Localisation Satellites
	LWE: Generated by Laboratoire d'Etudes en Geodesie et Oceanographie Spatiales, Collecte Localisation Satellites
	LSWT: University of Reading LSWT processor version v2.6.1-146-gfe50b81_RES120
	LIC: Lake ice cover processor by H2O Geomatics
	LWLR: Calimnos processor by Plymouth Marine Laboratory, including calls to Idepix (SNAP) and POLYMER (Hygeos) algorithms
references	http://cci.esa.int/lakes
tracking_id	f5170cc0-0da7-4b2b-b829-93e485aa451a
conventions	CF-1.8

Attribute	Value
product_version	V 2.1.0
Format_version	CCI Data Standards v2.3
Summary	This dataset contains L3S daily ECV Lakes products: Water Level (LWL), Water Extent (LWE), Ice cover (LIC), Surface Water Temperature (LSWT) and Water Leaving Reflectance (LWLR). L3S data are observations combined from multiple instruments into a common spatiotemporal grid
keywords	Satellite, Lake, Climate Change, Lake Water Level, Lake Water Extent, Lake Surface Water Temperature, Lake Ice Cover, Lake Water Leaving Reflectance
id	ESACCI-LAKES-L3S-LK_PRODUCTS-MERGED-20190214-fv2.1.0.nc
naming_authority	lakes.esa-cci
keywords_vocabulary	inspire: INSPIRE spatial data themes, gcmd: NASA Global Change Master Directory (GCMD) Science Keywords, gemet: GEMET keywords
keywords	Satellite, Lake, Climate Change, Lake Water Level, Lake Water Extent, Lake Surface Water Temperature, Lake Ice Cover, Lake Water Leaving Reflectance, Orthoimagery, EARTH_SCIENCE-OCEANS-OCEAN_OPTICS-WATER-LEAVING RADIANCE, EARTH_SCIENCE-TERRESTRIAL_HYDROSPHERE- WATER_QUALITY_WATER_CHEMISTRY-CHLOROPHYLL, SUSPENDED_SOLIDS, TURBIDITY, water, algal bloom, aquatic environment, freshwater, freshwater quality, ice, inland water, lagoon, lake; dam; phytoplankton; turbidity, water monitoring, water quality, water reservoir, climate; seasonal variation, environmental data, environmental monitoring, monitoring, remote sensing,
cdm_data_type	Grid
comment	These data were produced for the ESA Lakes_cci project
date_created	2022-02-22
creator_name	ESA Lakes_cci
creator_url	https://climate.esa.int/en/projects/lakes/
creator_email	lakes_cci@groupcls.com
project	Climate Change Initiative - European Space Agency
geospatial_lat_min	-90.0
geospatial_lat_max	90.0
geospatial_lon_min	-180.0
geospatial_lon_max	180.0
geospatial_vertical_min	NA
geospatial_vertical_max	NA
time_coverage_start	19920101T120000Z

Attribute	Value
time_coverage_end	20191231T120000Z
time_coverage_duration	P1D
time_coverage_resolution	P1D
standard_name_vocabulary	CF Standard Name Table v78
license	ESA CCI Data Policy: free and open access
platform	LWL: TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, Sentinel-6A, Envisat, SARAL, GFO, Sentinel-3A
	LWE: Landsat-<4,5,7,8>, Sentinel-1A
	LSWT: ERS-2, Envisat, Metop-A, Metop-B, Sentinel3A, Sentinel3B, Terra
	LIC: Aqua, Terra
	LWLR: Aqua, Envisat, Sentinel-3A, Sentinel-3B, Orbview-2, Suomi NPP
sensor	LWL: Poseidon-1, Poseidon-2, Poseidon-3, RA, RA-2, AltiKa, SRAL
	LWE: MSS, TM, OLI
	LSWT: ATSR-2, AATSR, AVHRR-3, SLSTR, MODIS
	LIC: MODIS
	LWLR: SeaWifs, MODIS, MERIS, VIIRS, OLCI
spatial_resolution	1 km at Equator
key_variables	water_surface_height_above_reference_datum, lake_surface_water_extent, lake_ice_cover, lake_surface_water_temperature, chla_mean, turbidity_mean, Rw[xxx] where xxx is one of 400, 412, 443, 469, 490, 510, 531, 547, 560, 620, 645, 665, 674, 681, 709, 754, 779, 859, 885, 900, 1020nm
geospatial_lat_units	degrees_north
geospatial_lon_units	degrees_east
geospatial_lat_resolution	0.008333333
geospatial_lon_resolution	0.008333333
doi	10.5285/7fc9df8070d34cacab8092e45ef276f1

Appendix B - Example of Global attributes for LIT files

Attribute	Value
title	CCI-LAKES Lake Ice Thickness dataset. LRM_LIT data analysis over the Great Slave Lake for pass 45 and JASON-1, JASON-2 and JASON-3 missions
institution	Collecte Localisation Satellites
source	CNES, NASA, EUMETSAT, NOAA
history	"Generated by Collecte Localisation Satellites
references	https://climate.esa.int/en/projects/lakes/
Conventions	CF-1.8
product_version	V1.0
summary	this dataset contains LIT information over Great Slaves lake
keywords	Satellite, Lake, ice thickness
id	ESACCI-LAKES-L3C-LIT-GreatSlave_Pass45.nc
naming_authority	lakes.esa-cci
comment	These data were produced for the ESA Lakes_cci project
creator_name	ESA Lakes_cci
creator_email	lakes_cci@groupcls.com
project	Climate Change Initiative - European Space Agency
standard_name_vocabulary	CF Standard Name Table v78
license	ESA CCI Data Policy: free and open access
platform	Jason1, Jason2, Jason3
key_variables	LIT
latitude	latitude of the center of the LIT ROI: 61.49 degrees_north
longitude	longitude of the center of the LIT ROI: 115.04 degrees_west
time_coverage_start	20020116T231528
time_coverage_end	20220330T050143
doi	10.5285/7fc9df8070d34cacab8092e45ef276f1