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Detecting climate-related shifts in lakes: A review of the use of satellite Earth Observation

Elisa Calamita,[1*] **J. Jelle Lever**,[1,2] **Clement Albergel**,[3] **R. Iestyn Woolway**,[4] **Daniel Odermatt**[1]

[1]Eawag, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland
[2]WSL Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland
[3]European Space Agency Climate Office, ECSAT, Oxfordshire, UK
[4]School of Ocean Sciences, Bangor University, Wales, UK

Abstract

Climate change exerts a profound impact on lakes, eliciting responses that range from gradual to abrupt transitions. When reaching critical tipping points, the established lake dynamics stand to undergo substantial modifications, setting off a chain reaction that reverberates through the entire ecosystem. This lake shift ripples into related ecosystem services and even influences the well-being of human communities. Despite the importance of lake shifts, we lack a systematic overview of their occurrence, mainly due to the lack of systematic data at the global scale. We reviewed the literature focusing on climate-related lake shifts and assessed how satellite Earth Observation (EO) has contributed to the research topic, and what we can unlock from this novel data. Our results show that EO data are used in only 9% of studies on lake shifts, although this fraction has increased since 2012. EO data is most commonly used to assess shifts in surface extent, ice coverage, or phytoplankton phenology. These variables are directly observable and the spatio-temporal resolution of EO satellites is of great advantage. But lake shifts can also be identified indirectly from EO data, as in the example of the vertical mixing of lake water, which can be described on the basis of surface patterns. In all possible applications, we expect increasing use of EO satellites in the future, including the development of early warning systems that promise to provide timely alerts regarding impending lake shifts, thus serving as a vanguard against abrupt alterations that could ripple through interconnected ecosystem services.

There are over 117 million lakes in the world (Verpoorter et al. 2014) and they are recognized as key sentinels of climate change, reflecting physical, chemical, and biological responses to climate-induced changes within the lake catchment as well as the overlying atmosphere (Adrian et al. 2009; Williamson et al. 2009*a*,*b*). Moreover, lakes play an important role in local and regional climate regulation (Balsamo et al. 2012), providing destabilizing positive and stabilizing negative feedbacks within the climate system (Lenton et al. 2008). Thus, lake variables are considered Essential Climate Variables, as defined for the Global Climate Observing System (Woolway et al. 2020).

Lakes are changing rapidly in response to climate change (Woolway et al. 2020; Yao et al. 2023; Zhang et al. 2023), and those changes can occur gradually or can oftentimes be abrupt, without warning, and could even trigger abrupt transitions in the state of ecosystems when tipping points are passed (Scheffer et al. 2001*a*, 2009; Milkoreit et al. 2018; Mesman et al. 2021). Exceedance of such critical thresholds may result in abrupt changes in different lake processes, referred to as lake shifts, leading to a cascade of ecological and environmental consequences, from disrupted trophic linkages to altered food webs (Wagner and Adrian 2009; Hébert et al. 2021). For example, the long-term lake surface water temperature warming showed both at local (Austin and Colman 2007; Zhang et al. 2014; Salmaso et al. 2018) as well as global scales (Schneider and Hook 2010; O'Reilly et al. 2015; Sharma et al. 2015; Piccolroaz et al. 2020) can seriously impair biological processes when potential thermal limits are reached or exceeded (Till et al. 2019; Kelly et al. 2020; Dokulil et al. 2021). Lakes and freshwater systems are often dominated by ectothermic organisms which are very sensitive to changes

*Correspondence: elisa.calamita@eawag.ch

Additional Supporting Information may be found in the online version of this article.

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in environmental temperature and, therefore, likely to experience profound impacts (Thackeray et al. 2016; Till et al. 2019; Kraemer et al. 2021). Moreover, model simulations suggest that lake surface temperatures will continue to rise this century, with physical implications including shifts in stratification phenology throughout the northern hemisphere (Woolway et al. 2021*a*). Climate can indeed entail transitions in the mixing regime of lakes, altering the frequency or duration of mixing/stratification (Woolway and Merchant 2019; Toffolon et al. 2020; Woolway 2023). A reduction in mixing intensity and frequency can have severe implications for the entire lake ecosystem. For example, reduced deep-water renewal, which typically takes place during periods of homothermy, hinders the vertical transport of oxygen from epilimnion to hypolimnion and can increase the extent and duration of seasonal hypoxia (low oxygen) (Jane et al. 2021). In contrast, longer stratification can suppress nutrient resupply from deep water to the surface layer (North et al. 2014) with effects on the lake primary productivity and the entire food web (Yankova et al. 2017; Dakos et al. 2019). Furthermore, climate-related shifts can alter the timing and the probability of the clear water phase, a period of reduction in algal biomass and increased water transparency (Scheffer et al. 2001*b*; Ray et al. 2023). Also, those shifts can increase the browning of lakes, as a result of higher dissolved organic carbon concentrations (Monteith et al. 2007) with large effects on biodiversity, fish production, biogeochemical processes and drinking water quality (Weyhenmeyer et al. 2016). Thus, the dynamics of entire food webs may be profoundly affected by these climate-driven regime shifts (Scheffer et al. 2001*b*).

The characterization of lake shifts, and their attribution, is highly relevant and requires scientific evidence; however, this can be particularly challenging. Lake ecosystem shifts are of considerable interest because they might affect several ecosystem services provided for human well-being such as provision of safe water for drinking and irrigation, recreational use, and economic benefits, such as fisheries and tourism, with knock-on impacts on local economies (Woolway et al. 2022*b*). Especially because lake shifts may not appear gradually, but rather will occur quickly and often without warning, leaving little time for adaptation. However, research on tipping points and regime shifts in lakes poses unique challenges because of the many possible responses within lake ecosystems. Some climate-related shifts, such as fluctuations in lake level and shifts in the timing of ice formation and melt are clearly visible in lakes. Other signals, such as community changes in organisms for instance, may be equally sensitive to climate but more difficult to detect, as well as their impacts on the ecosystem services that lakes provide. Moreover, such variable climate-related shifts occur at different spatial–temporal scales, thus, the data to characterize them are of different types. To date, the main source of data to detect lake ecosystem shifts are sediment coring and trend analysis of high-frequency measurements (Binding et al. 2018; Xu et al. 2020). However, understanding the drivers of regime shifts often requires long and dense times series, and nowadays the availability of in situ records to characterize shifts in ecosystem structure or their underlying mechanisms is relatively low (Preston et al. 2016; Taranu et al. 2018; Woods et al. 2022).

Data obtained through satellite Earth Observation (EO) may provide a solution to data scarcity. EO largely contributed to the availability of global lake observations in recent decades (Palmer et al. 2015; Dörnhöfer and Oppelt 2016) and have been pivotal for many studies about lakes and climate change (Adrian et al. 2009; Zhong et al. 2016; Zhang et al. 2020; Calamita et al. 2021). Satellites can indeed detect changes in water temperature, water quality and color as well as ice cover and water quantity, as demonstrated by many recent studies (e.g., Woerd and Wernand 2015; Woolway et al. 2021*a*; Zhang et al. 2023). Lake surface water temperature is available at near daily frequency and with an accuracy of about 1°C which is highly appropriate to resolve seasonal variations and long-term trends (e.g., MacCallum and Merchant 2012). However, thermal sensors with daily revisit have only moderate to low spatial resolution in the order or 1 km^2. But the temporal revisit time of future high-resolution thermal missions (Landsats, Sentinel-8, Trishna, SBG) will soon lift this limitation. Water quality monitoring is more challenging because it changes much faster than temperature, thus standard observables (chlorophyll, dissolved organic matter, total suspended matter) may fail to represent relevant processes and they come with very high uncertainties. Water quantity can be observed with altimeters as extent changes, the former it was strongly limited in spatial sampling until last year's launch of the SWOT mission. Moreover, EO makes data available to researchers in a very cost-effective way. EO data are indeed systematically acquired, routinely processed, archived, and often made available from agencies at no direct cost. A fitting example is provided by the European Space Agency Climate Change Initiative Lakes dataset (Carrea et al. 2023), an openly available climate data record of globally distributed lakes.

This study delves into the role of EO in the detection of climate-related lake shifts and the potential insights it can unlock. In lake remote sensing research, climate change related trend assessments are explored extensively, but how much has EO contributed to detecting and studying climate-related lake shifts? For which specific scope have EO be used in climate-related lake shift studies? Where are the barriers in using EO for climate-related lake shift research? To answer to these questions, we performed a systematic review. We particularly focused on studies reporting climate-related lake shifts in recent scientific literature. This scope implicitly excludes a very large number of studies on the general use of EO data for monitoring lake water quality (*see*, e.g., IOCCG 2018), but it includes only those studying explicitly climate-related lake shifts, or, more specifically, the biological, physical and chemical parameters used to identify them. We further review the methods used to sample these parameters, namely in situ measurements, paleolimnological analyses, modeling and EO and we performed an in-depth text analysis of the latter group of studies. We also applied networking analysis on the literature dataset in order to identify research fields and key papers. Finally, we discuss the identified research gaps in climate-related lake shift analysis using EO and we discuss possible research directions and strategies to better explore EO in the context of lake shifts.

Methodology

Literature selection

A literature search in Web of Science (https://www.webofscience.com/wos/woscc/advanced-search) was performed to construct the literature dataset presented and analyzed in this study. The search terms were decided after exploring alternative keyword combinations with the aim of identifying all potentially relevant studies while minimizing the number of studies beyond the scope of our review (*see* all steps in Supporting Information Fig. S1). The three search terms: "regime shift," "critical transition," and "tipping point" were selected because, based on the paper from Milkoreit et al. (2018), they were found to be the most common search terms in shift-related research across disciplines. A 2nd list of keywords was selected by making a priori random choice of relevant papers that we used as a reference for the relevance of keywords. Most notably, the words "anomaly," "incomplete overturning," "incomplete mixing," "mixing regime" and "stratification phenology" were added to the previous list of keywords. For the sake of clarity, when searching for a phrase instead of unique word, we did not use quotation marks so any combination of search terms would be considered by the searching algorithm. We exported all returned articles from Web of Science (from 1900 until the end of 2021) which resulted in 888 candidate studies, out of which we discarded studies that did not directly focus on lake shifts related to climate change. For example, we discarded studies that purely assessed climate reconstruction, vegetation changes, river regime changes (hydrological or thermal), fauna property changes (ex. Turtles' shells) or lake changes, if not driven or related to climate change. After this filtering, we obtained a dataset of 449 studies that met the above criteria for inclusion in our literature review (Supporting Information). The described methodology is not limitation-free and might have missed some studies in the field of climate-related lake shifts; however, the final number of studies is comparable to the one that a recent review on tipping points in aquatic ecosystem found for lake studies (357 studies in Carrier-Belleau et al. 2022).

Literature dataset analysis

For each of the selected studies, we identified several properties. First, we identified the main data source used to identify and/or analyze the lake shift. Often more than just one data source is used and, in that case, the data source predominantly used to identify the lake shift has been chosen to describe the study, the other data sources are reported as complementary data sources. We then identified the main shift feature that was reported in the studies. A shift is indeed a multifaceted concept, and we identified the shift feature (or tipping element in lakes) that is taken as focus in the study, namely the biological, physical, and chemical parameters used to identify the specific shift. The aforementioned shift features are strongly linked to each other, and this can make their classification sometimes ambiguous. For example, changes in turbidity that could be classified as a physical feature could also be the result of a shift in the relative abundance of phytoplankton and macrophytes, which is a biological feature. Likewise, climate-related changes in nutrient availability may cause shifts in phytoplankton communities, which in turn can have a feedback on the nutrient budget (Tu et al. 2021). In addition, we identified the time window of the analyses (in years) and the number of lakes over which the study took place, also specifying the geographical location of the case studies. A full list of the studies together with the identified properties is reported in the Supporting Information.

We performed quantitative and qualitative analysis of the dataset that helped us highlight trends and patterns. We analyzed the geographical distribution of case studies in our literature dataset as well as the publication dates of all the reviewed publications over time. Moreover, we analyze the link between data sources and shift features in all the reviewed studies. We then conducted an in-depth text analysis of studies using EO to detect climate-related lake shifts. Particularly, we screened each paper singularly to obtain a detailed picture of how EO data have been used to-date in this research field. Finally, we applied the clustering method described in Newman (2006) to group publications into clusters based on their relations and to identify research areas or scientific fields. This method creates clusters by partitioning the papers in our dataset, represented as nodes in a network, into a number of groups. Papers belonging to the same cluster share more links among each other, while they share fewer links with the papers outside of their cluster than can be expected on the basis of random chance (i.e., when links are distributed randomly) (Newman 2006; Šubelj et al. 2016). Two types of networks were analyzed. The first, in which papers were considered linked if they had at least one keyword, as provided by the authors, in common except when this keyword was also a search term. The 2nd involved a network in which papers were linked when they had at least one common citation.

Results and discussion

Data sources across space and time

The 449 studies in the literature dataset detect and analyze lake shifts by using four different data sources (Fig. 1A). The largest pool of studies uses in situ data (> 40% of studies), meaning data directly collected at the lake, such as water samples, probe measurements, sediment samples or fauna counts.

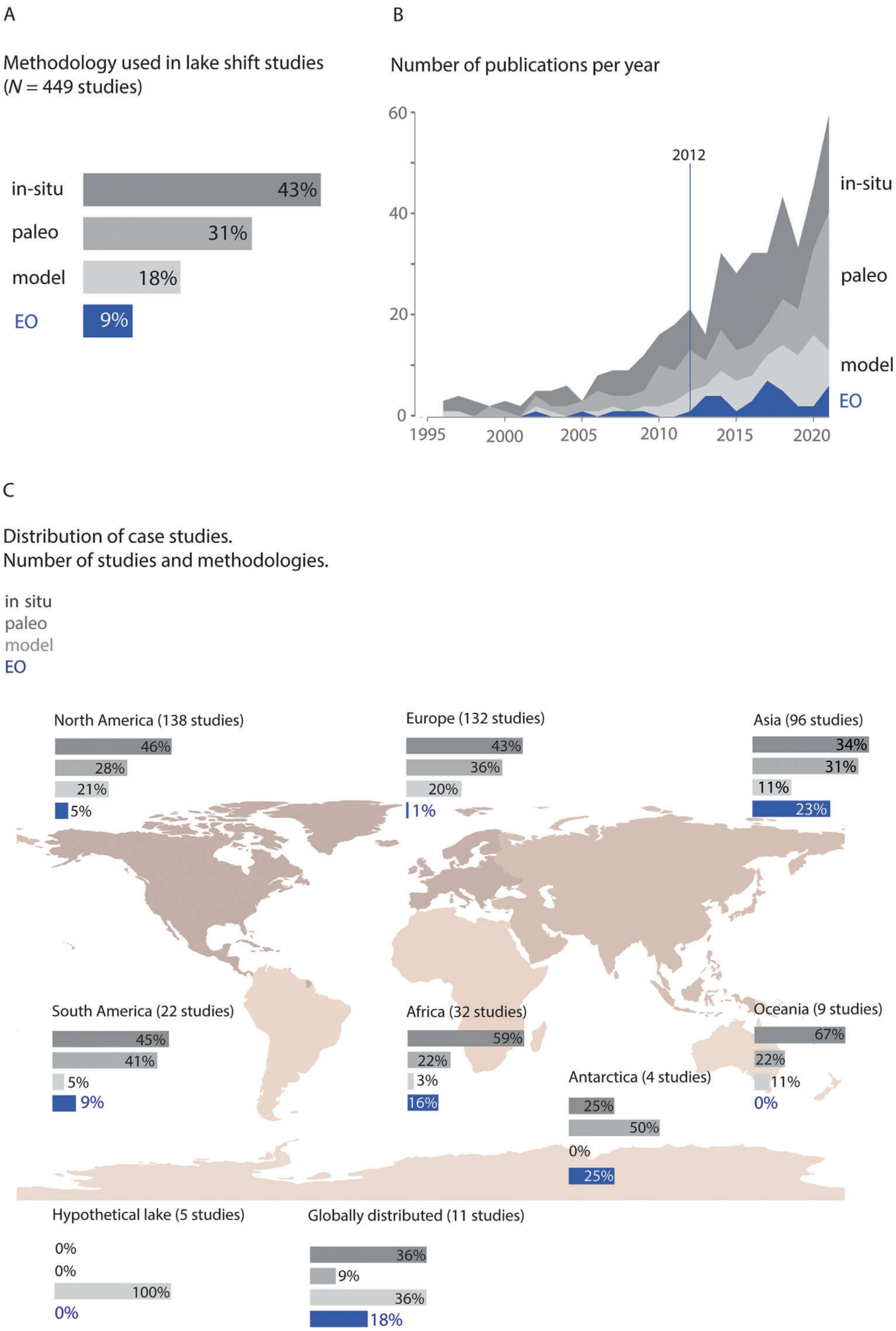


Fig. 1. (**A**) Percentage of studies using the different data sources: in situ measurements, paleolimnological data, models, and satellite EO (in blue). (**B**) Temporal distribution of the appearance of studies in our literature dataset (1996–2021). Studies are aggregated based on the main data source used to analyze the lake shift respectively. (**C**) Geographical distribution of the lakes analyzed in the studies. The bar plots report the percentage of studies using each specific data source in the respective continents. "Hypothetical lake" indicates studies that are based on a hypothetical rather than an actual lake, and "Globally distributed" indicates studies that analyze lakes worldwide.

Such data can be collected following different strategies and using different spatial or temporal resolutions. The 2nd largest pool of studies use paleolimnological data to detect lake shifts (> 30% of studies). Paleolimnological studies focus on reconstructing the past biological, chemical, and physical status of inland waters using geologic records, namely sediment cores retrieved at the lake bottom (Smol 2010). After dating the different layers of the sediment core, paleolimnological data refer to the core depth as a time axis. Depending on the length of the core, different time spans of lake history can be reconstructed. A 3rd class contains the studies that use modeling tools to detect and analyze lake shifts (18% of studies). Very different types of models are included in this class: from 0D lake models (no spatial dependency but only time dependency; e.g., Elliott 2012), to 1D models that are able to, for example, reconstruct the vertical profiles of water quality in time (Bruce et al. 2018; Bartosiewicz et al. 2019; Woolway and Merchant 2019; Christianson et al. 2020; Christianson and Johnson 2020); to more complicated 3D models (Caramatti et al. 2020; Biemond et al. 2021). The time resolution of such models can also differ, ranging from sub-daily to yearly depending on the model structure and on the specific research question of the study. Finally, we found that EO data are by far the least used data source in the studies that we reviewed. Only 9% of the analyzed studies used EO as the main data source to detect or analyze lake shifts.

All studies in the literature dataset were published between 1996 and 2021 and during this period the number of publications increased exponentially (Fig. 1B). The 1st exact search term that appeared in 1997 was "anomaly," followed by "incomplete mixing" in 2003, "regime shift" in 2006. Then, "tipping point" and "critical transition" appeared both in 2011 and last "incomplete overturning" in 2019. Interestingly, in this literature dataset, the term "tipping point" and "critical transition" appeared during the same year and only 5 yr later in comparison to "regime shift," while across all scientific disciplines, the first became popular after the year 2000 long after the terms regime shift and critical transition (Milkoreit et al. 2018).

EO is not only the least represented data source used to analyze lake shifts, but it is also the one that appeared most recently (Fig. 1B). The regular use of EO data for lake shift studies started only in 2012, after occasional use in the decade before. This is consistent with the fact that the use of radar, optical and thermal remote sensing for lakes has increased sharply in the past 10–15 yr as a consequence of improvements in sensor resolution (Palmer et al. 2015; Dörnhöfer and Oppelt 2016; Topp et al. 2020). This period contains also the 1st full archive analyses of the ENVISAT mission, the revival of the Landsat series 14 yr after Landsat-7 and, perhaps more importantly, the transition from storage media to online distribution and analysis. Finally, the free access to Landsat data (released for free public use in 2008) has been integral. Cloud computing also facilitates the analysis of spatio-temporally comprehensive EO data, but evidence for its use remains sparse in our literature dataset.

The studies included in our review cover a global distribution of lakes (Fig. 1C). They encompass many different lake types, and they range from shallow wetlands like the Pantanal floodplain in South America (Silio-Calzada et al. 2017) to large lakes such as the Laurentian Great Lakes (Fichot et al. 2019) in North America or Lake Baikal (Katz et al. 2015) in Russia. Some studies refer to natural as well as artificial lakes, to hypothetical lakes or to lakes spread around the world (Fig. 1C). Interestingly, the share of EO is largest in remote and less traditionally monitored areas (Antarctica, Himalaya, Africa) as well as global studies.

Shifts as a multifaceted concept

Limnology has a physical, chemical, and biological foundation (Lapierre et al. 2020) and ecosystem shifts can appear in multiple variables across these disciplines, but scientific studies on these shifts typically fall within one of them. We therefore classified the studied shift features as physical, chemical, or biological (Fig. 2). Out of the 449 reviewed studies, 59% of them analyze lake physical shift features, 33% report biological shift features and only 8% report chemical shift features and although in varying quantities, EO studies occur in all the three different classes (Fig. 2).

Physical features reflect changes in the lake physics driven by lake shifts. Since the early 1990s, there is evidence about the impact of climate change on lake temperature (Magnuson et al. 1990; Schindler et al. 1990). The fact that surface water temperature increases and that it increases faster than deep-water temperature (Pilla et al. 2020; Jansen et al. 2022) results in an increase in thermal stability that might lead to an increase in the duration of stratification in summer and a corresponding decrease in the duration of homothermy in winter and spring (Livingstone 2003). Moreover, at high latitudes and altitudes where lakes experience ice cover, increasing surface water temperature leads to changes in ice phenology, especially for ice-off, and often with a decreasing duration of ice cover (also having then positive feedback on increasing stratification; Sharma et al. 2021). The combination of these effects could imply a shift in the mixing regime of lakes. Deep monomictic lakes may experience years with reduced intensity of mixing, in which stratification persists throughout the year becoming oligomictic and shallow polymictic lakes, instead, may lose their winter ice cover and thus may undergo permanent mixing during winter (Woolway and Merchant 2019). Other examples of physical features of lake shifts are changes in sedimentation rate in lakes (Watanabe et al. 2009) or abrupt changes in lake extent. We classified as "extent" all the studies that refer to shifts in lake water level or in lake extent as they refer to the same phenomena (Bai et al. 2021). As for instance in the case of a sudden shrink of lake extent (Zhao et al. 2017) or to a sudden formation of new lakes, for example, from glacier melting (Sun et al. 2018; Shugar et al. 2020; Stuart-Smith et al. 2021). Among those physical features, EO data have been used so far to study shifts in lake extent, ice cover and mixing regime while shifts in thermal regime and sedimentation was so far investigated only using other data sources.

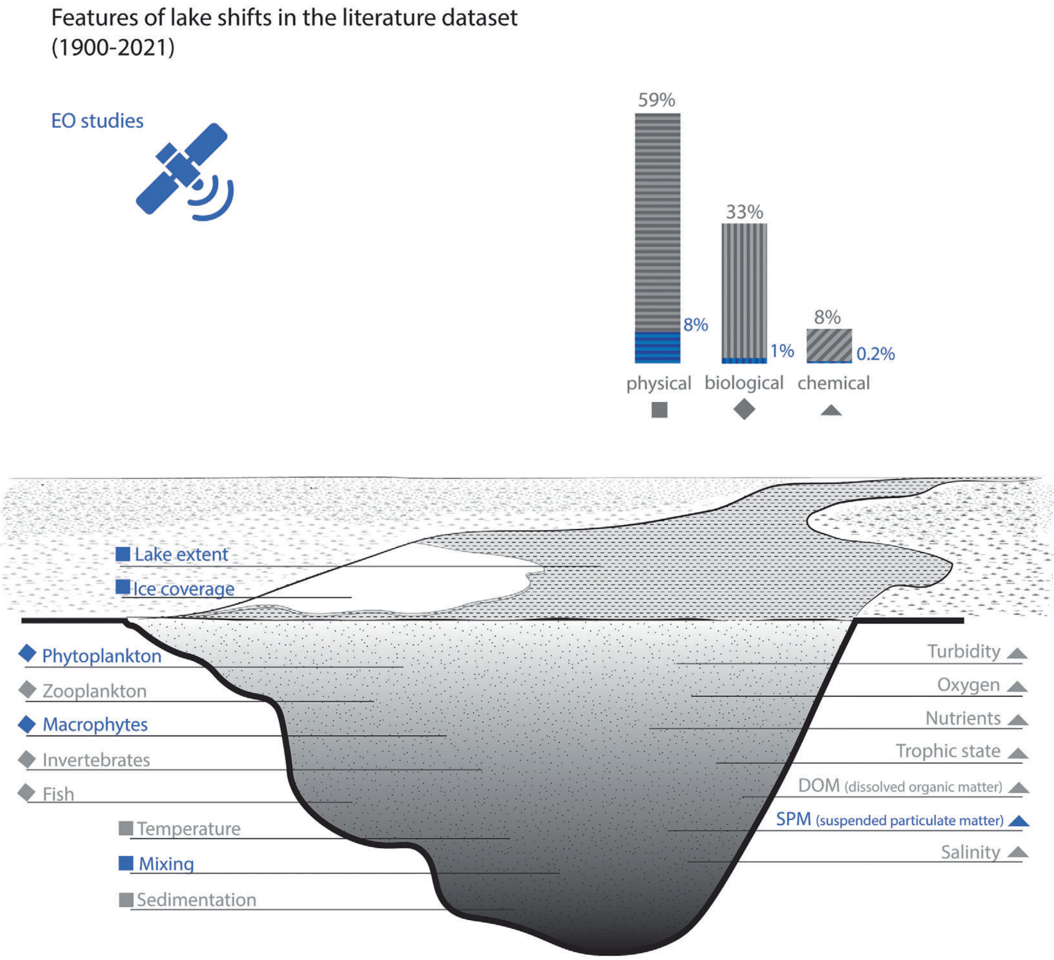


Fig. 2. Features of climate-related lake shifts reported in all the reviewed studies and their classification in three classes: physical (59%), chemical (8%) and biological features (33%). Blue color highlights the features that have been studied by using satellite EO as main data source.

Chemical features of lake shifts relate instead to changes in water quality. Climate change may indeed affect water quality through direct or indirect processes. The enhanced and prolonged stratification may lead to changes in the oxygen regime of lakes due to depletion of dissolved oxygen in the hypolimnion (Müller et al. 2012). Through hydrological alterations, climate changes may affect the water renewal rate in lakes with major shifts in the physical and chemical properties of waters (Adrian et al. 2016) such as turbidity and organic matter content. Moreover, climate change could lead to major shifts in nutrient concentrations: for example, reduced mixing leads to reduced nutrient availability in the epilimnion (Salmaso et al. 2018; Schwefel et al. 2019) or also, lake deoxygenation would have subsequent effects on nutrient mineralization and phosphorus release from lake sediments (Rogora et al. 2018). Chemical features of lake shifts are the least explored using EO, only shifts in suspended particulate matter (SPM) have been so far studied using primarily EO.

Finally, other studies focus more on the biological features of lake shifts, notably on the effect of lake shifts on the lake living organisms. Climate change has, indeed, the potential to alter community structure and lake ecosystem functioning. Shifts may occur in phenology, species and size distribution, food-web dynamics, life-history traits, growth and respiration, nutrient dynamics, and ecosystem metabolism (Adrian et al. 2016). One of the most common biological features, which has been documented in many shallow lakes, is the transition from macrophytes to algae (clear to turbid state; Huang et al. 2021). Other important biological features of lake shift are changes in fish community structure (Bao et al. 2021; Su et al. 2021). Such changes can have cascading effects in lakes, most implying increased predation on larger zooplankton, which in turn means less grazing on phytoplankton and in consequence higher algal biomass per unit of available phosphorus (Jeppesen et al. 2010; Meerhoff et al. 2012). In other cases, the predatory effect is reversed if the prevailing or additional predators are invertebrates that prefer small prey (Adrian et al. 2016). Thus, stronger predation because of higher temperature leads to a stronger removal of small species (Hessen et al. 2013). Also, warmer water temperature and prolonged stratification can lead to higher phytoplankton biomass, particularly higher biomass of cyanobacteria during summer (Phillips et al. 2021). Among those only shifts in phytoplankton and macrophytes have been so far studied using primarily EO.

Linking shift features and data sources

Different features of lake shifts are preferentially studied using specific data sources. EO are mainly applied when assessing the physical features of lake shifts (Fig. 3). Among the different physical shifts, the detection of lake extent shifts seems to be the most common aim for which remotely sensed data have been used so far. On the other hand, paleolimnological data are mainly applied when studying the biological features of lake shifts (Smol et al. 2005; Michelutti et al. 2015*a*,*b*). However, in the case of paleolimnology as well as in situ and modeling studies, the use of data to detect the different shift features are less uneven than in EO studies. Interestingly, physical features are the preferred type of shifts detected by in situ, modeling and EO, but the 1st two sources of data are mainly applied to detect mixing regime shifts in lakes, while EO is mainly applied to detect shifts in lake extent.

The temporal scales of the different lake shifts and data sources can partially explain the fact that specific features of lake shifts are preferentially detected by specific data sources. Lakes' responses to climate changes occur on various temporal scales. Physical consequences of lake shifts such as variation in temperature and mixing regimes span sub-daily to monthly time scales while shifts in species composition occur at daily to yearly time scales (Adrian et al. 2016). Thus, the application of different data sources to study distinct shift features is also linked to the time span and time resolution of the different data sources.

Different data sources provide differents trade-off between temporal scale and spatial coverage. The analysis of the

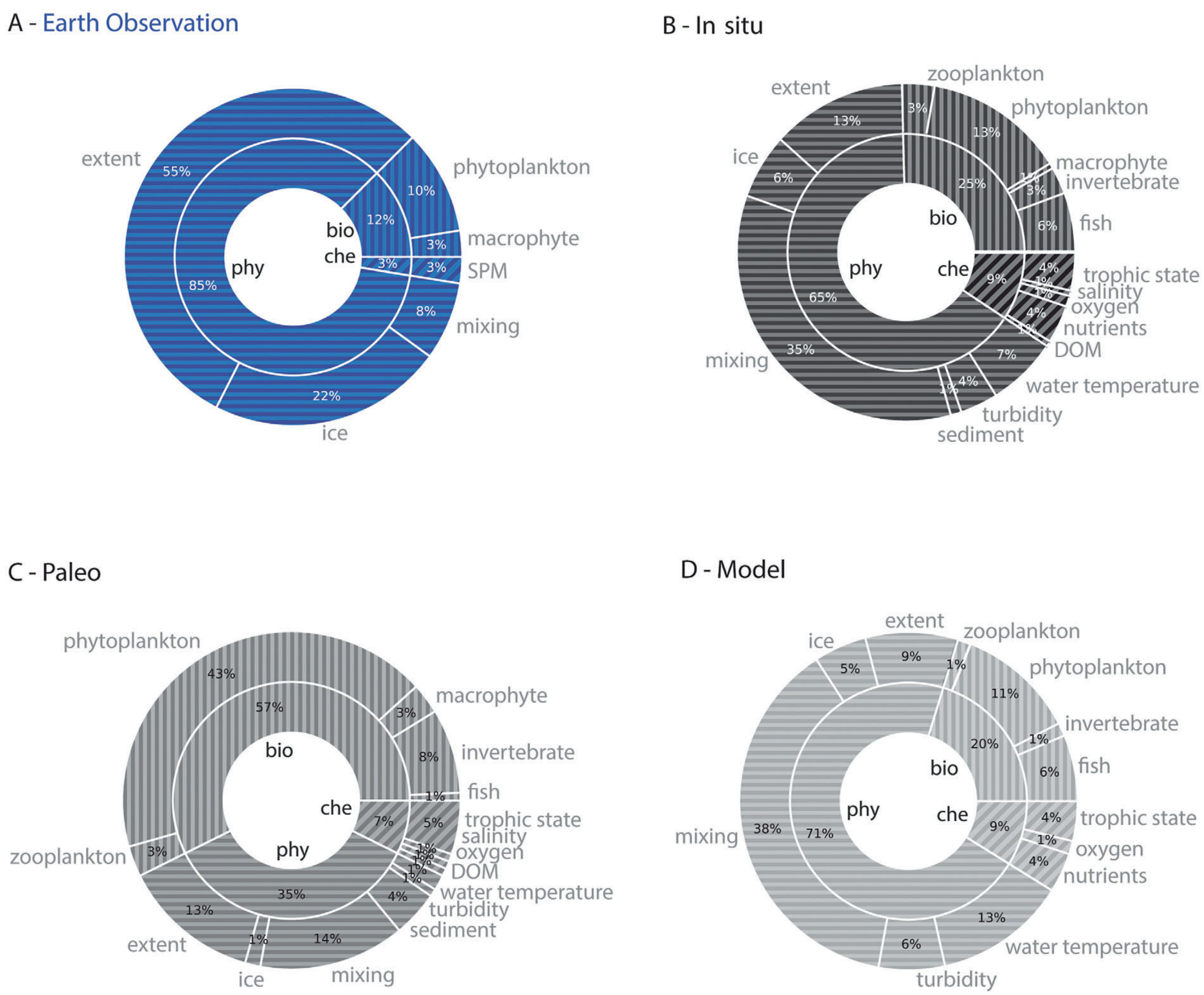


Fig. 3. Climate-related lake shift features identified by means of different data sources: (**A**) EO, (**B**) in situ, (**C**) paleo, and (**D**) modeling. The different features of lake shifts are classified as physical (phy, horizontal line pattern), chemical (che, vertical line pattern) or the biological (bio, oblique line pattern). The 2nd circle of the pie charts shows the breakdown of all features of lake shifts found in the literature dataset.

timespan as well as the number of case studies assessed in each paper of the literature dataset show that EO have the highest median spatial-scale (Fig. 4, median of 4 and max of 13,300 lakes per study, Šmejkalová et al. 2016), meaning that EO allows the potential to investigate more lakes at once. However, this comes at the expense of the time period of study, the median time span of EO studies is the shortest (median of 4 and max ∼ 50 yr for pioneering work, Chowdhury et al. 2021), expected due to its more recent appearance. On the contrary, paleolimnology allows reconstructions until several millennia (median of 1080 yr). The long-term historical records and reconstructions from sediment cores (paleolimnology) have indeed yielded insight into less visible climate-related changes, thus increasing understanding of the mechanisms driving these changes (Adrian et al. 2016). However, sediment coring requires intense fieldwork, usually constrains the number of lakes that can be studied at one time (median of 1 lake per study, *see* Fig. 4). In situ data and models are in between these two extremes; they analyze a smaller number of lakes than EO studies and a shorter time-span than paleolimnological studies. However, some exceptions can be identified. First, in situ studies contain reviews that incorporate data from previous studies, which comprise significantly larger numbers of lakes than those using only original data. For example, Schallenberg and Sorell (2009) statistically assess lake shifts in 95 New Zealand lakes by merging limnological observations from previous publications. Second, modeling studies often use remote sensing data for calibration or as model input, thus becoming similarly representative of larger numbers of lakes (Read et al. 2014; Woolway et al. 2019, 2021*b*; Woolway and Merchant 2019).

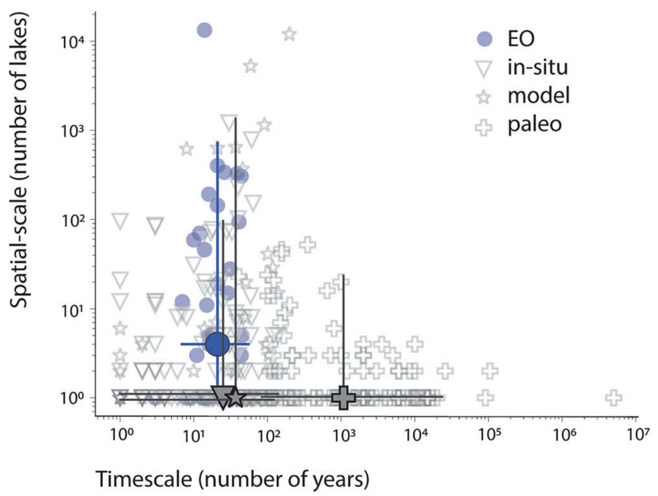


Fig. 4. Absolute number of years (past reconstruction or future scenario) and number of lakes analyzed in each of the studies contained in our literature dataset. The markers represent different data sources according to the legend. Highlighted markers show the median of the distributions and the segments report the 25th and 75th percentiles of the distributions, respectively.

A closer look at EO studies

The temporal analysis shows that EO is increasingly exploited to address features of lake shifts (Fig. 5). Two physical features prevail: lake water extent (Buma et al. 2018; Liang and Li 2019; Nitze et al. 2020; Bai et al. 2021; Chowdhury et al. 2021; Zhang et al. 2021), and ice cover (Sun et al. 2018; Wang et al. 2018; Carrea et al. 2023). However, during the last years few studies use EO also to address ecological shifts. In 2007, the 1st study using EO to address a shift in the

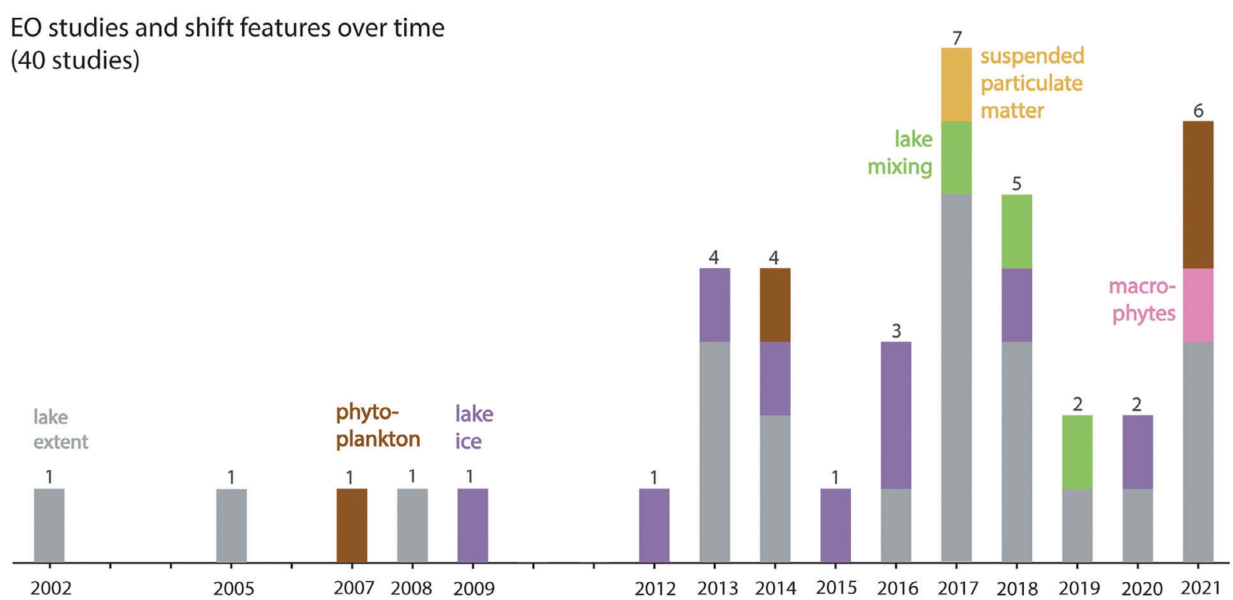


Fig. 5. EO studies and shift features analyzed in each EO study of the literature dataset over the period 1996–2021.

phytoplankton seasonality appeared (Bergamino et al. 2007). This study reports how phytoplankton studies focused mostly on point stations or lake transects over years, however the spatially distributed character of EO allows determining anomalies in chlorophyll related reflectance bands over years for the whole lake. Particularly, they use Empirical Orthogonal Function analysis to define regions with similar temporal covariation of phytoplankton biomass. In 2014, a 2nd study about tipping points in phytoplankton bloom using EO explained that EO is the only source of data providing a valuable tool to examine phytoplankton bloom initiation at a basin scale (Duan et al. 2014). Later, in 2021 two other studies reporting an ecological regime shift using EO were published. The 1st one (Free et al. 2021) uses EO to extract time series of chlorophyll *a* (Chl *a*) and then run a non-parametric multiplicative regression which revealed a change from spring to summer Chl *a* maxima. The 2nd study of Qin et al. (2021), instead, uses EO to generate time series and then perform an analysis of long-term trends. In 2021, another EO study reporting an ecological shift was published, this time assessing shifts in macrophytes (Damtew et al. 2021). Here, EO data were used to monitor spatiotemporal coverage of macrophytes and to classify macrophytes based on spectral bands.

During the last years, EO has been used also to assess shifts in lake mixing and SPM. We found three studies using EO to assess lake mixing. In the first one, EO helped extending the analysis of the mean lake surface water temperature and its summer amplified response to air temperature to a very large number of lakes worldwide (Woolway and Merchant 2017). In the other two studies (Woolway and Merchant 2018; Fichot et al. 2019), instead, the spatially distributed character of EO is the main reason of why EO were chosen as data source. They indeed analyze the spatial gradients of lake surface water temperature over time and draw conclusion base on this. Finally, we found only one study assessing a chemical feature of lake shift using EO where Cao et al. (2017) developed an algorithm to estimate the concentrations of SPM from EO which helped reveal transitions between pattern of SPM over years. A detailed overview of EO studies is reported in the Supplementary Information (*see* Supporting Information Table S1).

The use of EO as a main data source for studies related to lake shifts is strongly shaped by the history of EO satellites, as well as its strengths and weaknesses. The literature dataset reveals that the reason why EO data are the preferred choice for some studies is twofold: because of the spatially distributed character and because of the global coverage. EO allows 2D monitoring of the lake surface which otherwise would not be possible. Many of the EO studies in the literature dataset take advantage of this 2D property of data by for instance looking at lake extent change over time, lake ice coverage or lake surface water properties like surface water temperature (Woolway and Merchant 2018; Fichot et al. 2019) or SPM (Cao et al. 2017). Other studies, instead, choose to use EO either because of the remoteness of the case study so this is the only source of data available or because EO allows to extend the analysis to a very large number of case studies (e.g., Woolway and Merchant 2017). EO data offer, indeed, globally consistent observations for lakes for which in situ measurements are not available (Carrea et al. 2023). On the other hand, there are main weaknesses that cause the limited use of EO in the field of climate-related lake shifts. One important limitation of EO data is their relatively short temporal coverage because longer time series allow more robust trend analyses and higher the chance to detect shift-related signals. In our dataset, instead, we found that the maximum timespan covered by EO data is 56 yr (Chowdhury et al. 2021), much shorter than for other data sources and thus limiting the potential to detect lake-shifts. However, satellite data remain available for retrospective analyses and represents, like sediment cores and unlike in situ measurements, an information source that is unaffected of regional sampling biases and independent of the anticipation of lake shifts, thus this limitation will thus diminish with time. Another, more persistent limitation is the number of environmental variables that are accessible via EO, and the spatial resolution at which they can be retrieved. Sampling smaller areas means lower electromagnetic signals and in consequence smaller radiometric accuracy; improving technology may push but hardly lift this trade-off. However, the growing interest in using EO to track lake shifts is reflected by the increasing number of studies using such data, and by the increasing variety of shift features detected with EO. This recognition of satellite products for a growing range of applications is driving the development of new products. Requirements by the scientific community are indeed one of the primary drivers of development in the field, such as the ESA Climate Change Initiative.

Synergies between EO and other data sources

Many of the analyzed studies combine more than just one data source for their analysis (Fig. 6). We found that studies using in situ data to detect and analyze lake shifts are mainly using in situ data only and the same it is true for paleolimnological studies using only paleolimnological data. Instead, EO and models are mainly used synergistically with in situ data to study lake shifts because EO data, like models, often need a calibration/validation step or simply input data for which in situ observations are a requirement. In addition, EO and models can be used synergistically for the same purpose; many studies indeed use EO or a combination of EO and in situ data for calibration/validation of models. Such an approach has been widely explored in the last years to produce predictions of future lake surface water temperature all around the globe under future climate scenarios (Woolway and Merchant 2019; Maberly et al. 2020; Piccolroaz et al. 2020; Woolway et al. 2022*a*).

The synergy between EO and paleo data is instead less obvious and we found only three studies using paleo and EO (and in situ) data synergistically. Guerra et al. (2015) studies

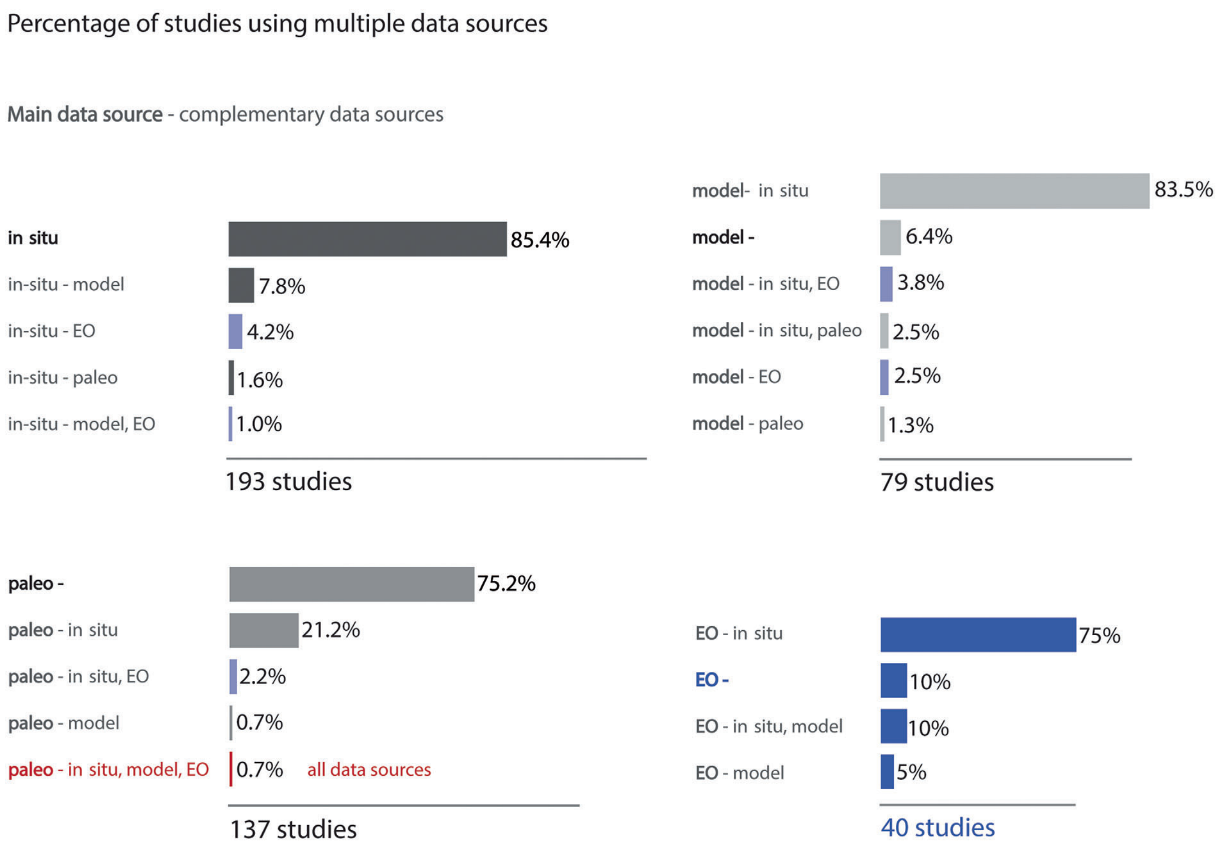


Fig. 6. Synergic use of different data sources for climate-related lake shift studies. The histograms show the relative number of studies using different main and complementary data sources.

a shift in lake extent due to a transition from wet to dry period. In this case, EO supports the study by providing images of the watershed, useful to track depositional areas in the catchment. Umbanhowar et al. (2011) studies the shift in sedimentation rate and the corresponding shift in lake productivity. Here the digital elevation model and digital raster graphic of the catchment supports the study by allowing the calculation of slopes within the catchment. This study focuses, indeed, on the factors driving the observed lake sedimentation changes, thus, the catchment properties are important. Finally, Huang et al. (2021) studies a shift of macrophytes by merging paleo, in situ, and EO. The different data sources were used to study the plant macrofossil, aquatic pollen concentration and the coverage of the whole lake respectively. An example of how different data sources can complement and verify each other, providing more comprehensive and accurate understanding of the evolution of macrophytes and revealing the long-term changes of macrophytes communities.

Only one study uses all four methodologies to analyze lake shifts. Lehnherr et al. (2018) combine all the four data sources, namely in situ, EO, modeling, and paleolimnological datasets to explain the ecological reorganization of the lake algal community assemblage in an arctic lake, Lake Hazen. In this study, different biogeochemical, limnological and ecological changes on the lake and watershed were tracked and EO were used specifically to study the lake ice phenology. The combination of different data sources allowed to demonstrate that accelerated melt in the cryosphere resulted in an increase of glacial meltwaters, sediment, organic carbon and legacy contaminants to Lake Hazen and a reduction in summer lake ice cover (Lehnherr et al. 2018). This study shows how the combination of more data sources allow to extend the analysis to more water parameters that are key to identify drivers of lake shifts. Moreover, linking EO with different data products is key to develop new ways of understanding when lake ecosystems approach critical transitions.

Clustering analysis: Interconnections among climate-driven lake shifts studies

Research fields

The keyword clustering analysis shows that there are five main keyword clusters in our pool of studies (Fig. 7). Keywords were reported for 335 out of 449 studies and out of these 335 studies, 277 had at least 1 keyword in common with 1 other paper. Thirteen clusters (i.e., modules) were initially detected using the method in Newman (2006); however, 8 of these clusters contained only few papers. The largest 5 clusters contained 240 papers in total and between 39 and 58 studies each (overall modularity equals 0.45). For each of these clusters, we report all keywords that occurred at least five times, and at least 5% as often as the most frequent keyword in each cluster (Fig. 7).

The most common keywords that bind the papers within these clusters together appear to correspond to five distinct research areas varying from paleolimnology, paleoclimatology, physical limnology, to water quality and ecology. For example, the keywords "phytoplankton," "zooplankton," "daphnia," and "macrophytes," in cluster 5 all correspond to different species groups. The papers in this cluster thus, likely, have an ecological focus. In cluster 3, the keywords "temperature," "ice cover," and "water level," point toward a focus on the physical properties of water bodies in these studies. The clusters "paleolimnology" and "paleo-climatology" share relatively many links between each other as indicated by the relatively short distance between them in Fig. 7. The research areas "physical limnology" and "ecology"

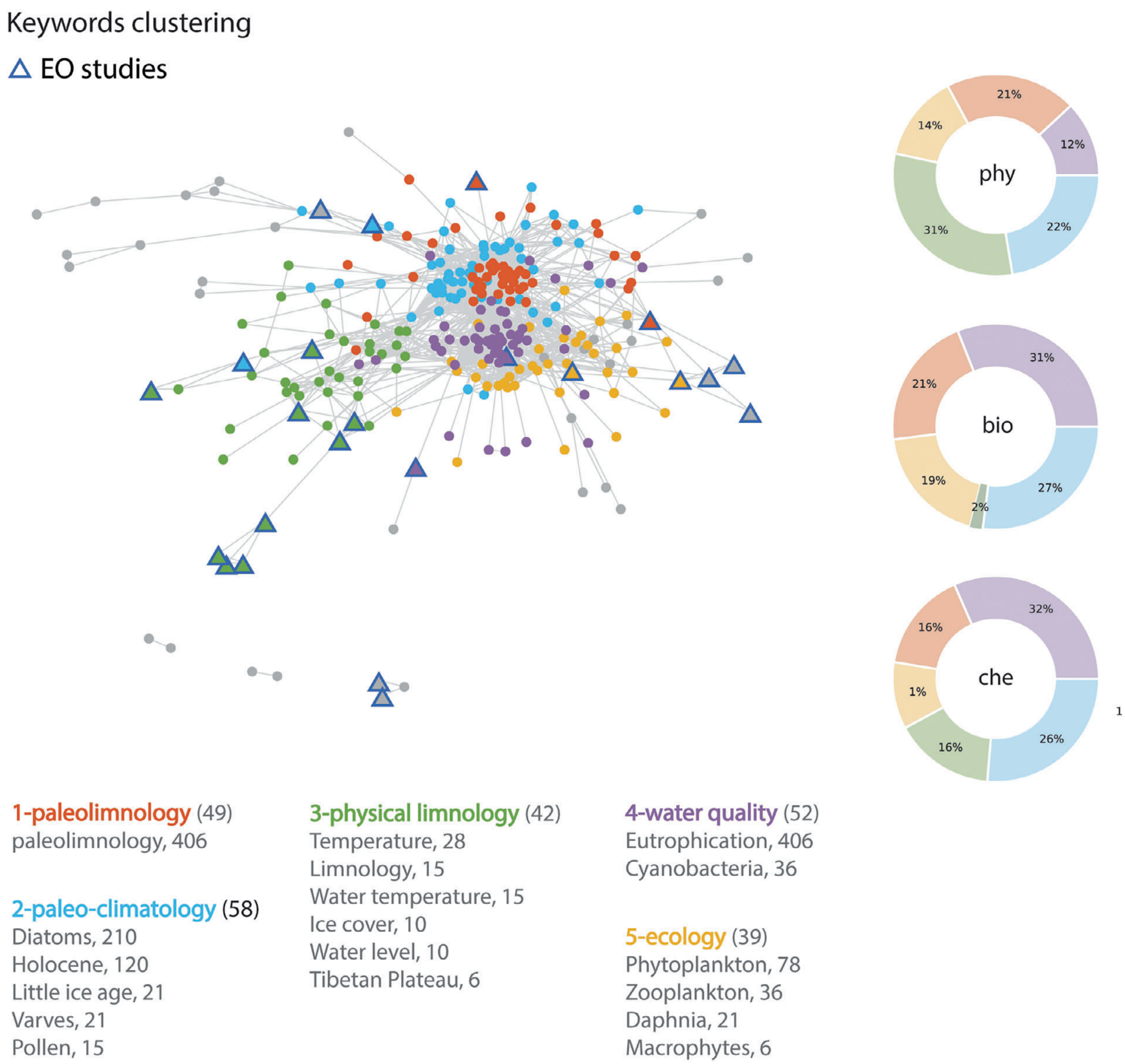


Fig. 7. Results of the clustering analysis using author keywords as connections between papers. Five main clusters or "research areas" were identified: paleolimnology, ecology, paleo-climatology, water quality, and physical limnology. The most common keywords that link the papers within each cluster are listed on the left. Interacting nodes (papers) are positioned relatively closely to each other while keeping a distance from other nodes using a force-directed drawing algorithm. The distance between clusters, therefore, roughly indicates the number of interactions shared between them and peripheral nodes are positioned relatively far from the center. The five identified clusters contain the share of physical, chemical, and biological shifts reported in the three pie charts, respectively, and they identify different research fields. EO studies are indicated by triangles with blue contours in the network. Gray dots are studies that do not fall within any of the five main clusters.

hardly share any common keywords and are located furthest away from each other, while the research area of "water quality" takes a fairly central position in between all five research areas.

The clustering analysis shows that the different features of lake shifts can be subject of different research fields within limnology. However, the share of physical, chemical, and biological features contained in each cluster also helped, to a certain extent, to identify the different research fields. Apart from the clusters of "paleolimnology" and "paleoclimatology" which have almost the same share of physical, chemical, and biological features; the "physical limnology" cluster has the highest physical features share; the "water quality" cluster has the highest share of chemical and biological features and finally the "ecology" cluster contain a higher share of biological features than physical and chemical. EO studies are spread throughout the five research fields with slightly more occurrence within the field of physical limnology. In general, however, they sit more towards the periphery of the network suggesting that, in terms of choice of keywords, they are only loosely connected to other papers. The full summary of relative percentage of data sources used in the different research fields are reported in the Supporting Information (Fig. S2).

Key papers

With a 2nd clustering analysis, we identify the most influential impactful studies that have influenced publishing trends in the field of climate-driven lake shifts during the last decades. For this aim, we performed a cross-citation clustering analysis on a network in which papers (nodes) were assumed to be linked when they had at least one reference in common. Out of the 449 papers, 443 papers shared a link with at least one other paper. Results show that there are three clusters (overall modularity equals 0.20) citing different papers. Details about these three citation clusters are reported in Fig. 8, where we report the three most cross-cited studies for each cluster together with the number of total citations.

The three key papers in the 1st cluster are paleolimnological studies. The 1st study shows how paleolimnological records from lakes in the circumpolar Arctic reveal widespread species changes and ecological reorganizations in algae and invertebrate communities in Arctic lakes since approximately 1850 (Smol et al. 2005). The 2nd study from Battarbee et al. (2002) instead provides a detailed description of how diatoms are used as indicators for environmental change and how numerical computing techniques allow the quantification of diatom–environment relationships. The 3rd study shows that recent climate change is the main driver for the recent success of small planktonic diatoms that have been reported in many aquatic systems (Rühland et al. 2015).

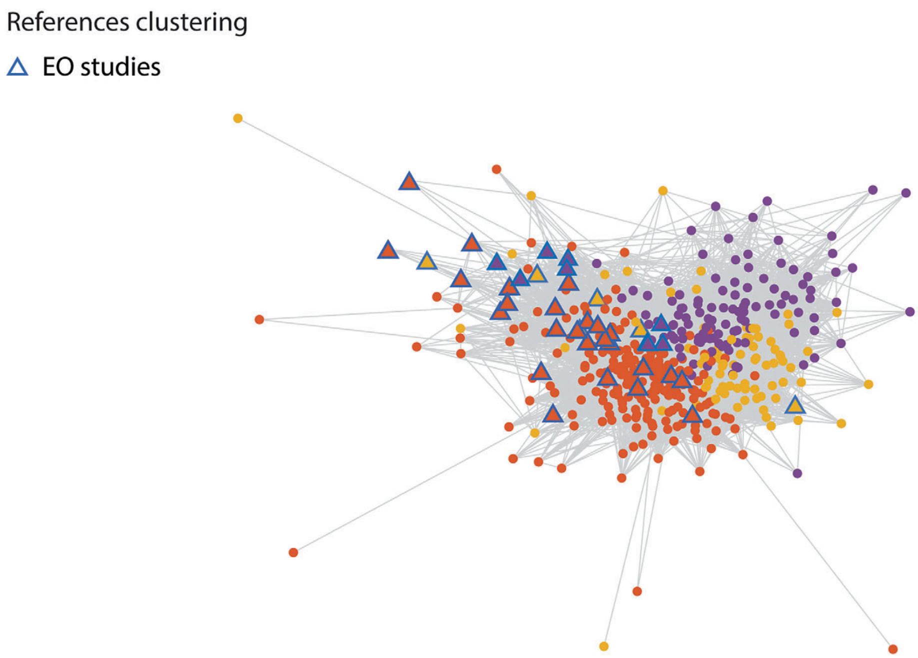
The three key papers in the 2nd cluster focus more on physical shifts, and they use mainly in situ data. The 1st, Adrian et al. (2009), identified the response variables within a lake that can be used as indicators of the effects of climate change in both, the lake and the catchment. The 2nd, Livingstone (2003), observed long-term changes in thermal structure of Lake Zurich (Switzerland), and using a one-box heat exchange model, he related them to shifts in the night-time rate of emission of infrared radiation from the atmosphere and in the night-time rates of latent and sensible heat exchange at the air–water interface. The 3rd, O'Reilly et al. (2015), presented the 1st worldwide synthesis of in situ and satellite-derived lake temperature data and it showed that lake summer surface water temperatures rose rapidly between 1985 and 2009, at a global average rate of 0.34°C per decade.

The key papers of the 3rd cluster are all from the same 1st author, M. Scheffer. In the 1st study, the authors show that the loss of resilience in ecosystems usually paves the way for a switch to an alternative state (Scheffer et al. 2001*a*). In the 2nd study, the authors link field observations with simple models and provide the "classical" example of regime shifts in shallow lakes from a transparent to a turbid state as nutrient inflow increases (Scheffer et al. 1993). This was the 1st example of a regime shift in ecosystems supported by field observations. In the 3rd study, instead, a review of emerging ways to link theory to observations is presented and the authors conclude that although field observations can provide hints of alternative stable states, experiments and models are essential for a good diagnosis (Scheffer and Carpenter 2003).

EO data are only used in one of the identified key papers and as secondary data source. EO studies are most common in cluster 2 and they sit relatively close to a group of papers that are a mix of modeling and fieldwork studies (*see* Supporting Information Fig. S3). Although this cross-citation analysis favors older papers, with seven of the most influential nine papers being published before 2010, thus, penalizing the more recent EO studies, we can conclude that EO studies appear not to be key in lake shifts analysis. However, given the increasing use of remote sensing for lake shifts analyses in the last decade, there seems to be a growing chance that future seminal studies will be based on this data source.

What are the missed opportunities when using EO to study climate related lake shifts?

From this review we learned that there are different ways in which EO can support lake shift studies. EO provides spatio-temporal data of many lake water properties that are key for physical, chemical, and biological features of lake shifts. This is a unique property of this source of data, not acquirable with in situ monitoring for instance. EO data also allow monitoring lakes globally, giving the opportunity to upscale to very large number of case studies and to study changes along environmental gradients using a space-for-time approach. EO data provides input for modeling exercises of different types, from thermodynamic models to ecological models or hydrological models. Finally, EO data provides a powerful capacity to characterize large scale patterns. When it comes to integrating EO data in limnology, the lack of vertical (along the lake depth) monitoring capacity of remotely sensed data has been one of



Cluster 1 (124)
1. Climate-driven regime shifts in the biological communities of arctic lakes (Smol et al. 2005) (1225)
2. Diatoms (Battarbee et al. 2002) (840)
3. Lake diatom responses to warming: reviewing the evidence (Rühland et al. 2015) (253)

Cluster 2 (233)
1. Lakes as sentinels of climate change (Adrian et al. 2009) (2145)
2. Impact of secular climate change on the thermal structure of a large temperate central European lake (Livingstone 2003) (946)
3. Rapid and highly variable warming of lake surface waters around the globe (O'Reilly et al. 2015) (903)

Cluster 3 (87)
1. Catastrophic shifts in ecosystems (Scheffer et al. 2001b) (351)
2. Alternative equilibria in shallow lakes (Scheffer et al. 1993) (136)
3. Catastrophic regime shifts in ecosystems: linking theory to observation (Scheffer and Carpenter 2003) (120)

Fig. 8. Results from the cross-citation clustering analysis. The number of studies in each cluster is reported together with the three most cited papers of each cluster.

the main concerns by limnologists for several decades. EO provides, indeed, spatially distributed information about water quality of the surface layer, but it does not provide any information about the water quality at discrete depths of the water column. However, the characterization of processes in the horizontal dimension (lake surface) and linking such spatial information with the processes happening along the vertical dimension of the lake, can lift this very limitation at least partially. Such an approach has indeed been widely used in different research fields (e.g., oceanography and climate research) and it should be better explored in limnology. Often limnologists use EO data to derive spatially averaged time series, discarding the precious spatial component of these data. For example, EO-based global analyses of lake surface water temperature are mainly based on spatial means, where each lake represents an entity and spatial averaging enables analyses of their temporal variability and trends (Woolway and Merchant 2019; Maberly et al. 2020; Piccolroaz et al. 2020). Such an approach was also chosen in the only one key paper partially using EO data, identified by the cross-references clustering analysis (O'Reilly et al. 2015). However, the spatial component of remotely sensed data is of high value and could reveal further information about lake ecosystems (Bresciani et al. 2011; Kiefer et al. 2015; Toffolon et al. 2020; Ignatius et al. 2022). Thus, improving the characterization of processes in the horizontal dimension to deduct related vertical gradients could open many new research directions on how to use EO data for physical and biogeochemical studies of lakes. However, EO data often contain gaps in space and time due to cloud cover or technical issues, and therefore this research line should proceed in parallel with gap-filling efforts that facilitate complete raster datasets and more sophisticated analysis.

Surface-layer information could also help to identify early warning signals that may precede ecological shifts (Carpenter et al. 2011; Gilarranz et al. 2022). As an example, combining lake surface water temperature and ecological variables could reveal ecological shifts through anomaly detection. Such approaches have been widely used in forestry studies and biosphere sector (Verbesselt et al. 2016; Liu et al. 2019; Forzieri et al. 2022) but are almost untapped by limnologists. However, these methodologies could be translated from forestry to lakes in particular because the type of EO data at the base of the analysis would be of the same type, spatially distributed properties over the case study.

Satellites are observing the Earth at finer and finer spatial scale and the previously discussed analysis can benefit from the fact that the spatial resolution of EO is increasing. New missions, carrying new sensors and technology able to monitor our freshwater systems with a much higher spatial resolution have already been launched during the last years (e.g., SWOT, Prisma) or will be launched in the near future. Their products in terms of EO data will help to refine currently used methodologies and will also allow to extend the analysis to a larger number to case studies, nowadays not covered by EO, for instance, because of their size. Increasing spatial resolution would also allow for the application of more oceanography techniques to lake systems. Moreover, new technologies and algorithm development will broaden the water quality parameters retrieved by satellites, broadening the features detectable via EO.

On the temporal scale, EO data allow a near real time monitoring of lake water properties. In principle, EO data can be available right after their acquisition, a property that is not common for the other data sources. In situ data often need time to be collected and time for further analysis and the same is true for paleolimnological data. On the other hand, models require time to run, and they need to be calibrated using data, which need in turn acquisition time. EO data or models based on EO data help reducing any delay between acquisition and delivery allowing to produce interpretation of events already during their occurrence.

Conclusions

EO satellites are used extensively for monitoring water quality in lakes (IOCCG 2018), but they have a large untapped potential in the context of lake shift analysis. So far, only 9% of the studies in this field use EO data as main data source and another 4% use EO data as complementary data source. The analysis of lake shift features revealed that the research question addressed in the lake shift studies are of different types. More than half of the studies in the literature dataset address questions related to shifts in physical features like shifts in lake extent, lake ice coverage, lake mixing regime, turbidity, sedimentation, or water temperature. Another 1/3 of the studies address questions related to shifts in biological features, like shifts between phytoplankton and macrophytes, shifts in zooplankton, invertebrate or also shifts in fish community. Finally, the remaining 8% of the studies address questions related to the chemistry of the lake, meaning shifts in nutrient availability or trophic state, salinity, oxygen regime, dissolved organic matter, and SPM.

EO data offer important advantages, thus, opportunities to develop new research directions. EO data allow a near real-time global monitoring of lake water properties useful to develop a near real-time global assessments of the prevalence of lake shifts, important to inform on the frequency and worldwide distribution of lake shifts, which carry important consequences for the entire lake ecosystems but also for human-related activities (Gilarranz et al. 2022). The near real-time availability of EO allows also to develop early warning systems, thus, to indicate when a lake shift is likely approaching. Finally, the consistent and continuous monitoring of worldwide lake shifts is key to enable making broader statements about the responses of lakes to climate change. Lakes are considered sentinels for climate change for a good reason, they are well-defined ecosystems; they respond directly to climate change and incorporate the effects of climate change within the catchment; they integrate responses over time, which can mute random noise; and they are distributed across many different geographic locations and climatic regions (Adrian et al. 2016). However, the large variability in lake morphology, geographic location, and catchment characteristics means that generalizing results obtained from single case studies to a wider range of lakes remains a challenge. EO is increasingly capable to address the challenges associated with the large variability in lake morphology, geographic location, and catchment characteristics, allowing us to obtain a global picture of climate-related impacts on lake shifts.

Data availability statement

Data available in article supplementary material.

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Conflict of Interest

The authors declare no conflict of interest.

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