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Investigating lake chlorophyll-a responses to the 2019 European double heatwave using satellite remote sensing

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ABSTRACT

Compounded weather events such as sequential heatwaves are likely to increasingly impact freshwater ecosystems in the future. Satellite-derived chlorophyll-*a* concentration estimates for 36 European lakes during a widespread double heatwave event in the summer of 2019 show that deep and medium depth lakes at higher latitudes displayed a synchronous chlorophyll-a increase with temperature, possibly as the result of an improved light climate resulting from increased stratification. Many deep or northern lakes had a notable response to the heatwaves. Warmer, southern shallow lakes had the most asynchronous response, tending to show a greater response to subsequent low pressure or storm events than to the heatwave itself. Chlorophyll-*a* peaks typically occurred five days after the peak of the heatwave for shallow lakes. For some shallow lakes, the sequential cycle of several heatwaves and low pressure events was found to punctuate the seasonal pattern of chlorophyll-*a*. Notably, in several of these nutrient-rich lakes the response to the heatwave was dwarfed by large algal blooms occurring later during the typical cyanobacterial bloom period in early autumn, underlining the importance of timing and phenology in response to heatwaves in addition to depth, latitude and trophic state.

1. Introduction

Lakes, despite comprising <1 % of the area of water on Earth, represent a vital resource providing essential ecosystem services globally such as drinking water, biodiversity and recreational use which can be linked to sustainable development goals (Likens 2010; Janssen et al. 2021). Historically, human settlements have been established alongside freshwater for water supply but continued urbanization and population increase has led to hydrological modifications, eutrophication and loss of ecosystem services (Grimm et al. 2008). The rate of species loss in freshwaters may be five times that of the terrestrial environment with key drivers being identified as invasive species, land-use change and climate change (Ricciardi and Rasmussen 1999; Sala et al. 2000). Climate change is projected to have a more pervasive and stronger effect in coming decades influencing land cover, nutrient cycling, hydrology, species composition and biodiversity (Cardoso et al. 2009; Carpenter et al. 2011).

An average increase in lake summer temperatures has been estimated at 0.34 °C per decade but there is a diversity of response at regional level most probably because of lake morphology (O'Reilly et al. 2015). While higher temperatures can lead to a direct increase in phytoplankton growth (Konopka and Brock 1978; Jöhnk et al. 2008), the influence of temperature rise on the structural functioning of the catchment or lake is often more significant than direct physiological effects (O'Neil et al. 2012). One key concern is the predicted increase in the frequency and intensity of cyanobacteria blooms (mass development of phytoplankton) as a result of eutrophication and warmer temperatures (Paerl and Huisman 2009; O'Neil et al. 2012; Huisman et al. 2018). Blooms are primarily driven by nutrients, especially phosphorus which has a key role in defining the upper limit or capacity for cyanobacteria development (Carvalho et al. 2013). Other factors are also key to controlling blooms such as grazing, lake residence time and in particular the light climate and stratification of the water column (Reynolds and Walsby 1975; Timms and Moss 1984; Carvalho et al. 2013; Havens et al. 2019). In Europe in 2003 for example, a summer heatwave bloom event in the Nieuwe Meer lake in Amsterdam was linked to an increased direct

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growth of cyanobacteria as well as increased water column stability, under which buoyant cyanobacteria species have a competitive advantage (Jöhnk et al. 2008).

Rapid changes in temperature can also have ecological implications. In 2019, air temperature rapidly declined to 19.8 °C from a 34.8 °C heatwave event (Free et al. 2021a). This poses a potential threat to ecosystems as interrupting a heatwave by low-pressure, i.e. cold and cloudy systems, that lead to a sudden decline in temperature and a period of low irradiance, particularly in eutrophic shallow lakes, disrupts metabolism leading to a rapid decline in primary production and significantly negative net ecosystem production lowering oxygen concentrations and can lead to fish fills (Jeppesen et al. 2021a). In temperate lakes, fish die-offs occur more frequently in lakes of higher temperature and during periods of extreme heat and such events are predicted to double by mid-century with implications for species displacement, size spectrum or even depopulation (Till et al. 2019). The IPCC predict that warming is set to continue with an over 90 % likelihood of a continuation of the increase in the frequency of heat extremes over the 21st century in Europe, especially in southern regions (Ranasinghe et al. 2021). Recent projections estimate that lakes will get warmer for longer periods, with heatwaves potentially spreading across multiple seasons (Woolway et al. 2021a). In some regions, heatwaves can add to existing pressure from drought which can lower lake levels and areal extent (both detectable from satellite images) resulting from reduced inflows, increased evaporation and extraction for anthropogenic purposes (Deoli et al. 2021; Młyński et al. 2021; Papa et al. 2022; Zhao et al. 2022). This can have significant implications for ecological functioning in the littoral zone and also lead to increased sediment resuspension in shallow lakes (Ludovisi and Gaino 2010; Evtimova and Donohue 2014).

In the summer of 2019, a widespread double heatwave event occurred in Europe resulting in one of the top five warmest summers since 1500 (Sousa et al. 2020). The first heatwave was centered around 25–29 June with temperatures largely 7 °C above average. The second event occurred between 24 and 26 July with record high temperatures documented, exceeding a 40 °C daily maximum for the first time in Belgium and the Netherlands for example. The heatwaves formed were caused by an area of high pressure blocked either side by low pressure systems in the west and east for an extended period, receiving hot air masses transported by southerly wind from Africa producing the heatwave. Such events are called an omega block, named after the Greek letter Ω, due to the resulting shape formed by the high pressure system in central Europe blocked either side by low pressure systems in the west and east (Copernicus Climate Change Service 2019; Xu et al. 2020). The increase in frequency of European heatwaves has been associated with the reduction in Arctic sea ice and Eurasian snow cover and is likely to continue during the next century (Zhang et al. 2020). Recently, the issue of compounded weather events, whereby multiple climatic drivers or hazards can produce higher risk of significant impact has received more attention. An atmospheric block producing a sequence of heatwaves is an example of a temporally compounding event and can have multiple impacts, for example, on crops, energy demand and human health which is often underestimated (Mitchell et al. 2019; Zscheischler et al. 2020). Exactly how such sequential extreme events may affect lake ecosystems has recently been identified as a knowledge gap (Jeppesen et al. 2021b).

In the context of lakes, we anticipate that a sequence of events such as one heatwave, followed by a low-pressure system followed by a second heatwave might result in more intense phytoplankton blooms. For example in a shallow lake system, periods of warm temperature can lead to increased internal loading, which if followed by storms allows nutrients to be mixed in the water column which can be added to by high rainfall bringing external loading from rivers (Søndergaard et al. 2003; Free et al. 2021a). A subsequent heatwave may then drive further growth, in particular of cyanobacteria given their high temperature optima, and calm weather with light wind can lead to surface accumulations given their positive buoyancy (Konopka and Brock 1978; Shi et al. 2017; Bresciani et al. 2020). The response is likely to be different in deeper lakes where heatwaves can promote increased stratification, thereby increasing phytoplankton biomass rapidly through the improved light climate. For example, a more stable stratification promoted by calmer wind in 2006 in lake Müggelsee (Germany) was postulated as the key cause for a significant bloom compared to 2003 which also had a similarly hot summer (Huber et al. 2012).

It is expected that a temporally compounded heatwave event should have a clear impact on the concentration and pattern of summer chlorophyll-a, that is likely to be also influenced by the trophic state, phytoplankton community composition and lake typology. Through the monitoring of chlorophyll-a dynamics, remote sensing allows unique insights by providing both synoptic and relatively high frequency observations (e.g. Neil et al. 2019). The aims and objectives of this paper are firstly to examine the satellite derived estimates of lake chlorophyll-a for any potential responses during the period of the 2019 double heatwave for 36 European lakes. Secondly, to assess how the response varies depending on latitude, total phosphorus concentration and lake mean depth.

2. Methods

2.1. Data sources

The chlorophyll-a concentrations for summer 2019 were extracted from satellite data from the European Space Agency (ESA) Climate Change Initiative (CCI) Lakes_cci climate data record version 1.1 (Crétaux et al. 2020) (https://climate.esa.int/en/projects/lakes/). Chlorophyll-a was derived from water-leaving reflectance data from MERIS and OLCI sensors onboard Envisat (2002–2012) and Sentinel-3 (2016-present), respectively (Simis et al. 2020) (see Table 1 for acronyms). Remote sensing of chlorophyll-a might be affected by significant uncertainties stemming from correction for atmospheric effects as well as a lack of algorithms that can be universally applied to waterbodies spanning several orders of magnitude in non-covarying substance concentrations (Simis et al. 2020; Liu et al. 2021). To improve data quality, chlorophyll-a values with an uncertainty <60 % were hence used for analysis (Free et al. 2021c). Data from the Lakes CCI project has shown good correspondence with *in situ* measurements that were recorded daily and detected increases that paralleled increasing cyanophyte abundance estimated by weekly microscopic counts for lake Trasimeno (Free et al. 2022). Data on total phosphorus and lake mean depth were obtained from Waterbase, the European Environment Agency database on water quality (https://www.eea.europa.eu/data-and-maps/data/waterbase-water-quality-icm-1) or from the Environmental data MVM database for Swedish lakes (SLU 2022), see https://miljodata.slu.se/mvm/ or from published literature. Total phosphorus is a measurement of the total phosphorus concentration in the water and as phosphorus is often the limiting nutrient in freshwaters, it is typically correlated with chlorophyll-a and used in lake trophic status classifications (Sakamoto 1966; Dillon and Rigler 1974; OECD 1982). Summary statistics and details of the included

Table 1
List of Acronyms used.

Acronym	Meaning
CCI	Climate Change Initiative
DOY	Day Of Year
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	Fifth major global reanalysis produced by ECMWF
ESA	European Space Agency
MERIS	Medium Resolution Imaging Spectrometer
OLCI	Ocean and Land Colour Instrument
TAM	Time Alignment Measurement
TP	Total Phosphorus

lakes are listed in Table S1. Climatic data on air temperature were obtained from ERA5, the fifth-generation ECMWF reanalysis for the global climate and weather (hourly data on single levels) [https://cds.climate.copernicus.eu/cdsapp#!/home]. All ERA5 data documentation is available online: https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation. Air temperature was used in the analysis as it provides a more responsive indicator of heatwave dynamics than lake temperature, which can be slow to respond owing to thermal inertia (Woolway et al. 2021b).

2.2. Statistical analysis

Statistical analysis (regression, correlation, ANOVA) and visualisation of the data was carried out with R (Wickham 2016; R Core Team 2019; Soetaert 2021). The timing of air temperature peaks were identified by fitting a lowess line (a locally weighted non-parametric smoothing method) to the dataset with a span of 10 % of the dataset and a window half-width of 5 days thereby allowing the identification of local maxima implemented in the R package zoo (Zeileis et al. 2022). The same method for peak identification was applied to chlorophyll-a but missing daily values were linearly interpolated. This should not alter the maximum value recorded but may reduce the accuracy of the result. However, the average frequency of satellite observation for the dataset was every 1.7 days over the study period which compares favorably with *in situ* large scale synoptic sampling efforts and far exceeds those recommended by EU policy (Council of the European Communities 2000; Moss et al. 2003; Donis et al. 2021) and is close to the suggested sampling frequencies of once every 2 days needed to detect short term disturbance in phytoplankton dynamics (Stockwell et al. 2020). Lake Albufera (Spain) was excluded from analysis as it uniquely had a very intense bloom with chlorophyll-a > 200 μg l^{-1} in early June before the heatwave events.

It is difficult to precisely define and attribute change between environmental drivers and phytoplankton populations in diverse lakes. However, it may be possible to broadly generalize the response to heatwaves and subsequent low-pressure systems or storms. One potential approach to this is to calculate the difference between the daily temperature and that of the corresponding long-term temperature (using a 1981–2010 reference period), positive and negative values (anomalies) will therefore reflect temperatures above and below average with extreme values indicative of heatwave or storm events. These values were then plotted against the chlorophyll-a and the slope of the relationship calculated whereby a negative slope indicates a decrease in chlorophyll-a with an increase in temperature anomaly whereas a positive slope indicates an increase with temperature anomaly.

In order to quantify the degree to which time series of air temperature and lake chlorophyll-a were temporally aligned we carried out a Time Alignment Measurement (TAM) for each lake during the heat wave period (Folgado et al. 2018). TAM values range from 0, indicating perfect temporal alignment to 3, indicating completely out of temporal alignment. Prior to calculation, each variable was standardized by the maximum for each lake.

3. Results

3.1. Lake characteristics

A total of 36 European lakes in a region extending from 64°N to 39°N, hence representing a significant latitudinal gradient across multiple ecoregions (from Boreal to Mediterranean), were available in the Lakes_cci climate data records (Fig. 1). The lakes largely fell into three groups by mean depth, either shallow: <7 m (1.7–6.2 m), medium: 7–15 m (8.3–15.2 m) or deep: >15 m (27–177 m). The concentration of average total phosphorus ranged from 2 to 155 μg l^{-1} and tended to be higher in shallower lakes (Table 2), having a negative Spearman rank correlation between mean depth and total phosphorus of −0.54 ($p <$ 0.001).

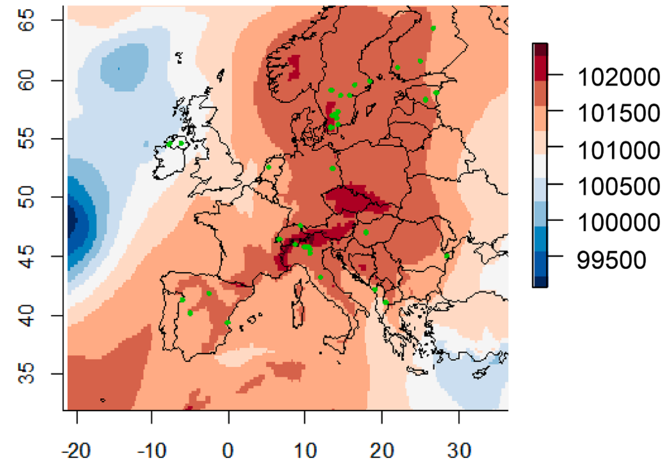

Fig. 1. Map of Europe showing 36 lakes (green dots) together with sea level atmospheric pressure (Pa) on the 24 July 2019 indicating the weather system that marked the peak of the July heatwave. Data sourced from ERA5. Longitude and latitude are in degrees. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Chlorophyll-a response

In order to examine the response of chlorophyll-a to the heatwave events, plots of the lakes for 2019 were first visually examined. Examples for lakes with shallow, medium and deep mean depth values are shown in Figs. 2, 3 and 4 respectively. Air temperature at daily resolution was plotted alongside the 30-year average (1981–2010) as well as satellite derived estimates of chlorophyll-a. We focused on the period covering the two heatwave events 14 June – 13 August (DOY 165-225). As indicated in the 2019 European state of the Climate report (Copernicus Climate Change Service 2019), the second heatwave event was more visible and centred around 25 July (DOY 206). For some shallow lakes, peak temperatures during a heatwave event appeared to coincide with a decline in chlorophyll-a. For example, in lake Võrtsjärv (Estonia, Fig. 2), as temperature increased during the second heatwave to 24 °C, chlorophyll-a declined from 36 (DOY 186) to 16 μg l^{-1} (DOY 209) before increasing to 34 μg l^{-1} following the storm or low-pressure event that ended the heatwave (DOY 214). Similarly in lake Trasimeno (Italy), larger increases in chlorophyll-a corresponded to low-pressure events associated with the end of heatwaves increasing from 12 (DOY 206) to 15 μg l^{-1} (DOY 214) but also following another event outside the main European heatwave with a 10 μg l^{-1} increase after DOY 225 that marked a step change to higher chlorophyll-a concentrations for that lake for the rest of the summer. In contrast for shallow lake Bolmen (Sweden, Fig. 2) results were more variable and a pattern less clear.

For the lakes of medium depth, the response to the second principal heatwave was mixed (see Fig. 3 for examples from 3 Swedish lakes) with lake Glan having an increase in chlorophyll-a after the heatwave whereas lake Ivösjön experienced a more synchronized increase in chlorophyll-a as temperatures increased. For lake Mälaren the chlorophyll-a was variable and had a less clear response.

In the deeper lakes of the Alpine region (Maggiore, Constance and Garda), which also tended to be more nutrient poor, having lower total phosphorus (TP) values (Table 2), the chlorophyll-a was always relatively low but nonetheless an increase in chlorophyll-a was visible in synchrony with rising temperatures from the first but not the second heatwave in 2019 (Fig. 4).

Some shallow lakes had notably large algal blooms in late summer /early autumn around DOY 250 (7 September) coinciding with the drop in temperature reflecting changing season. Examples are reported for lake Razim (Romania), Rosarito reservoir (Spain) and lake Balaton

Table 2
Summary statistics of the 36 lakes by depth group.

Depth group	<7 m (n = 16)			7–15 m (n = 10)			>15 m (n = 10)		
Variable	Median	Mean	Range	Median	Mean	Range	Median	Mean	Range
Total phosphorus μg l^{-1}	46.0	53.0	15–155	30	38	8–124	8	17	2–48
Surface Area km^2	86	270	6–2000	95	615	16–3509	363	979	11–5650
Mean depth m	4.4	4.2	1.7–6.2	10.0	10.4	8.3–15.2	104.0	100.0	27–177

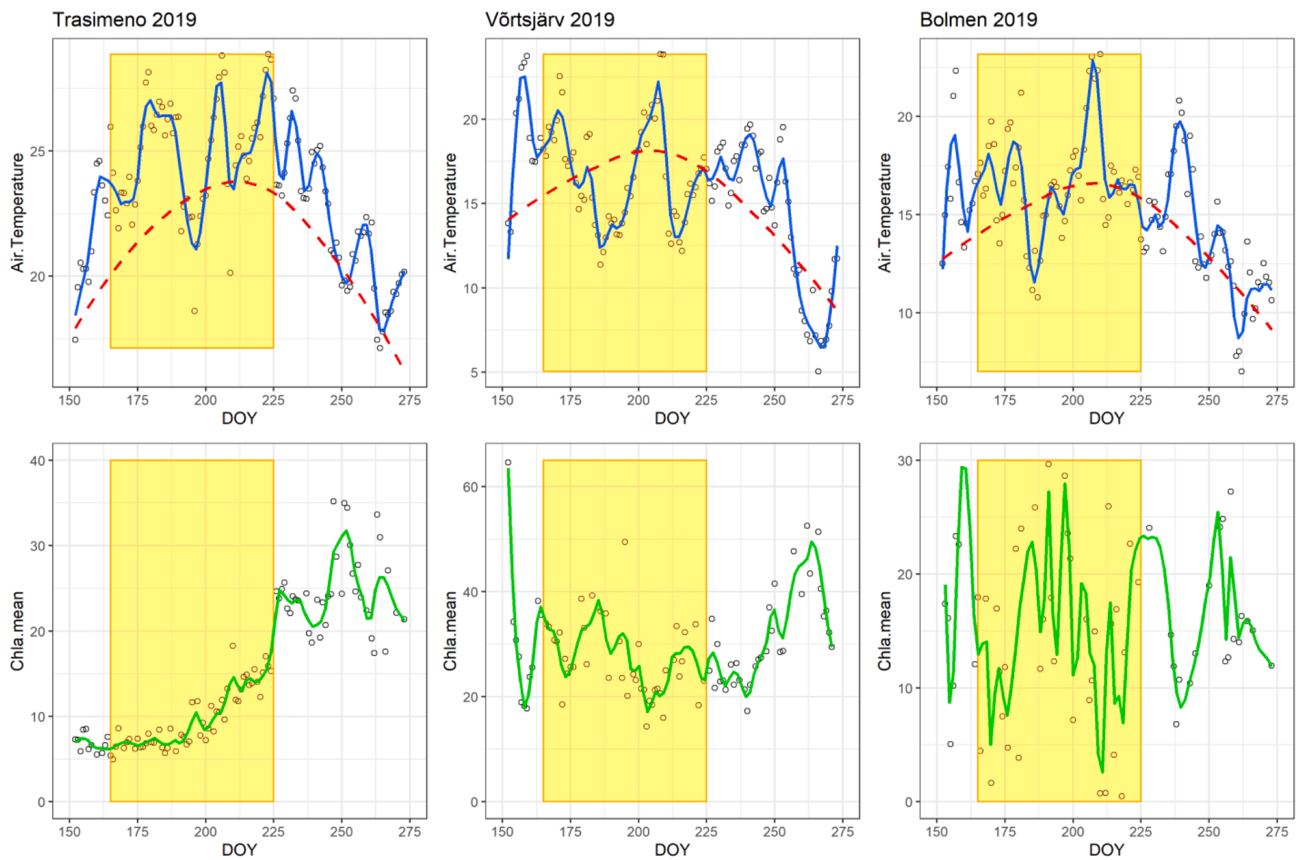

Fig. 2. Response of three shallow (<7m) lakes to the double heatwave event (Trasimeno (Italy), Võrtsjärv (Estonia), Bolmen (Sweden)). Top: Daily air temperature in 2019 (dots with blue smoothed lowess line) and average air temperature (°C) (1981–2010) (red dashed smoothed lowess line). Bottom: mean lake chlorophyll-a concentration (μg l^{-1}) in 2019 (dots with green smoothed lowess line). Yellow box highlights day of year (DOY) examined 165–225 (14 June – 13 August). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Hungary) (Fig. 5). These large increases were approximately-three or more times the concentrations observed during the heatwave period.

3.3. *Synthesising the response of chlorophyll-a to heatwaves and identifying additional factors*

To generalize the response to heatwaves and subsequent low-pressure systems or storms, for each of the lakes the chlorophyll-a concentration was regressed against its corresponding daily temperature anomaly. Negative slopes indicate a decrease in chlorophyll-a with an increase in air-temperature anomaly whereas positive slopes indicate an increase with air-temperature anomaly. Examining the calculated slopes indicated shallow lakes were typically negative, medium depth lakes were mixed between negative and positive whereas deep lakes showed little response with a slope close to zero (Fig. 6A). An ANOVA found evidence for a significant difference between these groups with Bonferroni post-hoc tests indicating a difference between shallow and deep lakes ($p = 0.03$). There was also a tendency, for lakes with higher TP to have a more negative slope (Fig. 6B) ($r_S = 0.53$, $p < 0001$) with the exception of the deep lakes.

In addition, we examined the air temperature peak for the second heatwave and identified the concentration and timing of the closest chlorophyll-a peak, either on the ascending or descending limb of the heatwave (Fig. 7). Peak chlorophyll-a concentrations were highest in the shallow lakes with highest concentrations found 7 days after the heatwave, whereas concentrations were lower in medium and deep lakes. Looking solely at the timing of the chlorophyll-a peak relative to the temperature peak, the median value was +5 days for shallow lakes, +5.5 for medium and −0.5 for deep lakes. In short, shallow and medium lakes tended to peak after the heatwave whereas deep lakes during or slightly before – indicating synchrony between temperature and chlorophyll-a peaks for deep lakes. In addition, chlorophyll-a peak concentrations identified during this heatwave were positively correlated with lake total phosphorus ($r_S = 0.59$, $p < 0.001$) and negatively with mean depth ($r_S = -0.65$, $p < 0.001$).

Time Alignment Measurement (TAM) values were calculated to indicate temporal alignment between temperature and chlorophyll-a with 0 indicating perfect alignment and 3 indicating completely out of temporal alignment. TAM values for the lakes investigated ranged from 1.75 to 2.85. A stepwise multiple regression was then carried out to see

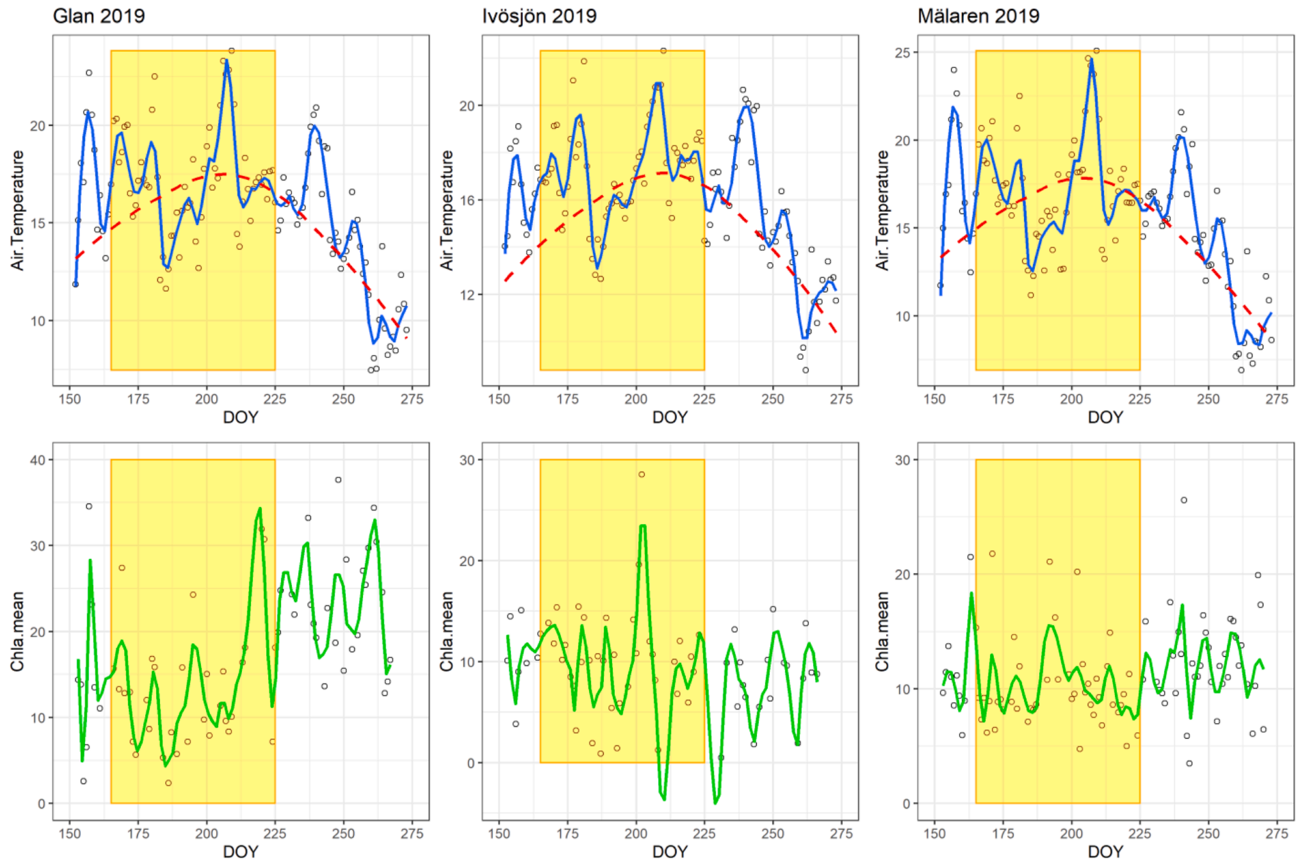

Fig. 3. Response of three medium depth lakes (7–15 m) to the double heatwave event (Glan, Ivösjön, Mälaren (Sweden)). Top: Daily air temperature in 2019 (dots with blue smoothed lowess line) and average air temperature (°C) (1981–2010) (red dashed smoothed lowess line). Bottom: mean lake chlorophyll-a concentration (μg l^{-1}) in 2019 (dots with green smoothed lowess line). Yellow box highlights day of year (DOY) examined 165–225 (14 June – 13 August). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

what parameters might control how much in phase or out of phase the two parameters were. Latitude was the variable that explained most variation with an R^2 of 0.37 which increased to 0.51 with the addition of log mean depth. Other variables analysed that were not significant in explaining additional variation included total phosphorus, summer average (2019) air temperature and log lake area. The regression indicated that shallower lakes at lower (warmer) latitudes tended to be more out of phase than deeper lakes at higher (colder) latitudes (Fig. 8).

4. Discussion

4.1. Response of chlorophyll-a to heatwaves and role of typology and nutrient status

The increase of air temperature in 2019 above average levels, in accordance with the two officially recognised consecutive heatwaves (Copernicus Climate Change Service 2019), was visible for most of the lakes in the dataset, in particular for the second heatwave. There was a different response of chlorophyll-a to the heatwaves depending on lake depth. The shallow lakes appeared to be either not affected or negatively affected during the heatwave event with a stronger response to the low-pressure and storm events that typically follow heatwaves. There were three strands of evidence for this, i) a strong negative slope with temperatures above average (i.e., a positive temperature anomaly), ii) tendency for chlorophyll-a to peak not during but around 5 days after the maximum heatwave temperature and iii) the tendency for warmer (lower latitude) shallower lakes to display most asynchrony with temperature and chlorophyll-a. There are several potential explanations as to why a greater increase in chlorophyll-a is observed after heatwaves in response to low-pressure events and storms in shallow lakes. Often summer storms can be associated with high rainfall bringing nutrients from catchment sources at a time when water temperatures and phytoplankton biomass are already high, resulting in rapid growth (Irvine et al. 2001). For shallow lake Trasimeno in Italy, satellite images have been used to trace such inputs and widespread bloom proliferation in 2018 (Bresciani et al. 2020). In addition, for shallow lakes internal loading of nutrients may also play a role as warm and calm weather during heatwaves can promote the mineralization and release of phosphorus as well as through resuspension during subsequent high wind events (Søndergaard et al. 2003).

The larger increase in chlorophyll-a observed in the shallow lakes is likely also a result of these lakes having higher concentrations of TP (Table 2) and a positive correlation was found with chlorophyll-a peak and TP. In Europe, examining larger datasets, it holds true that shallow lakes typically have higher TP as well as a higher productivity compared to deeper lakes afforded by the faster recycling of nutrients and less light limitation (Nõges 2009). Interestingly, a mesocosm study looking at the influence of nutrients, higher temperature scenarios and heatwaves on phytoplankton found that nutrients were the most important factor with biomass substantially higher regardless of temperature and heatwave treatment. The influence of higher temperatures and heatwaves was mostly observed in the low nutrient (<14 μg l^{-1} TP) treatments (Filiz et al. 2020). The very high nutrient group (>300 μg l^{-1} TP) was suggested to be less affected by the heatwave because it was already dominated by cyanophytes adapted to higher temperatures. However, in certain conditions, it has been found that a reduction in wind speed can cause a settling of sediments, increasing light and phytoplankton biomass (Janatian et al. 2020). This contrasts with our results where in

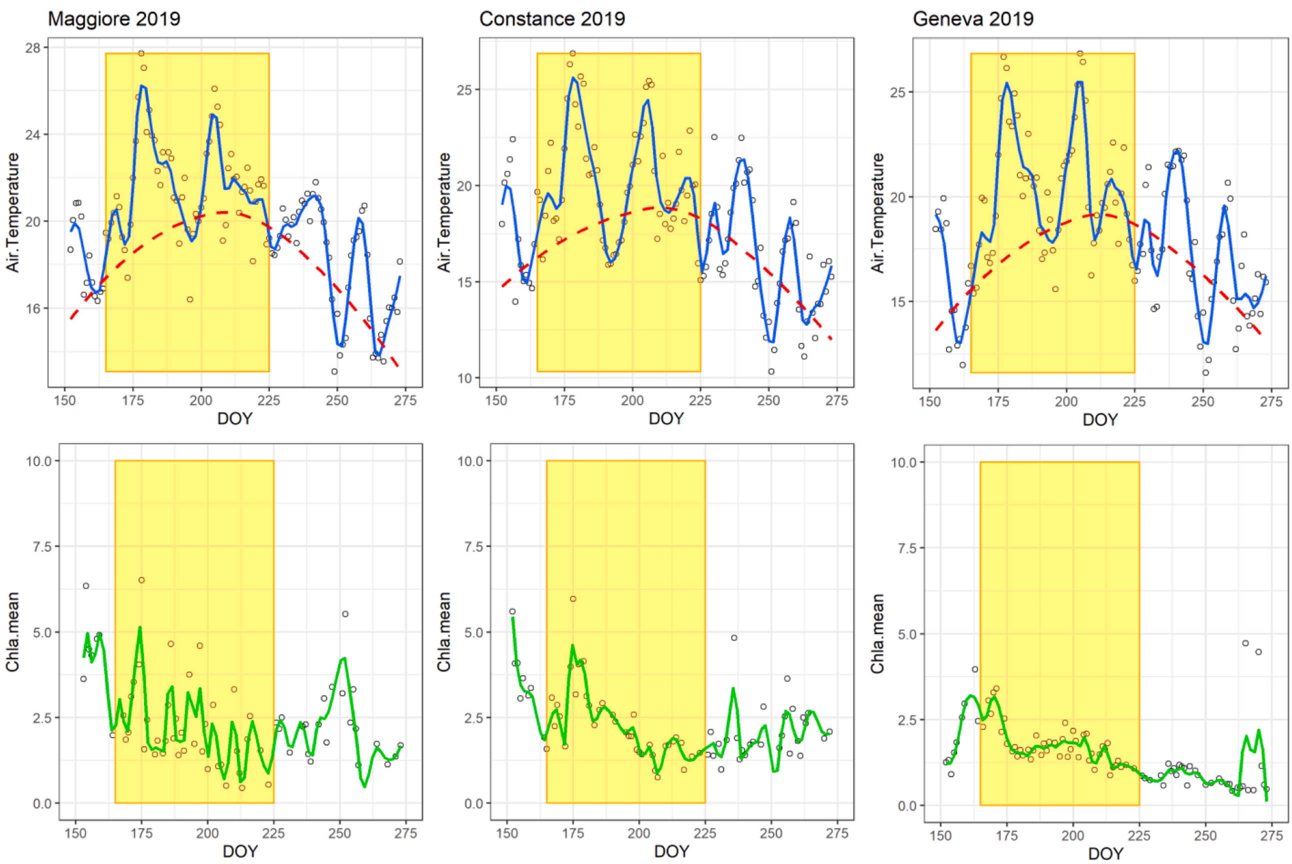

Fig. 4. Response of three deep lakes (>15 m) to the double heatwave event (Maggiore (Italy), Constance (Germany/Switzerland), Geneva (France/Switzerland)). Top: Daily air temperature in 2019 (dots with blue smoothed lowess line) and average air temperature (°C) (1981–2010) (red dashed smoothed lowess line). Bottom: mean lake chlorophyll-a concentration (μg l^{-1}) in 2019 (dots with green smoothed lowess line). Yellow box highlights day of year (DOY) examined 165–225 (14 June–13 August). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shallow lakes the heatwave period which would typically be characterized by calm weather, tended not to show an increase in chlorophyll-a until the successive low pressure and storm event. Heatwaves may be expected to have some short-term negative influence on photosynthesis, particularly at lower latitudes and for shallower lakes through photoinhibition from increased irradiance exposure, but this is also dependent on existing biomass, turbidity and depth that provide 'refuge' from photoinhibition (Belay 1981; Gerla et al. 2011). The importance of TP was also reflected in a global analysis of 2561 lakes where it accounted for 42 % of the variation in chlorophyll-a compared to 38 % for climate variables and 20 % for morphology parameters (Shuvo et al. 2021). High nutrients are often a feature of European lakes and a pan-European assessment indicated that diffuse pollution with excess concentrations of nitrogen, phosphorus and pesticides came mainly from agriculture and affected 38 % of surface water bodies. Other important pressures included atmospheric deposition, hydromorphological alteration, point sources, introduced species, abstraction and other anthropogenic pressures (Kristensen et al. 2018). However, it has been identified that European water policy needs to be updated to incorporate more detailed information on the influence of climate change in such assessments (Carvalho et al. 2019).

Medium depth lakes tended to show a variable response with the slope being positive or negative but typically smaller in value compared to the shallow lakes, a fact reflected in the lower chlorophyll-a concentrations observed before, during and after the heatwave (Figs. 6, 7). This contrasts with the deep lakes that had lower slope values centred on zero indicating a weak response with peaks more typically recorded during the ascending limb of the heatwave before the temperature maxima was reached. A lot of the dynamics of the response in medium and deep lakes is likely to be driven by stratification and the size of the available nutrient pool. For example, in lake Müggelsee (TP typically > 70 μg l^{-1}), despite relatively equal hot summers in 2003 and 2006 only 2006 showed a significant bloom, which was ascribed to a more stable stratification in 2006 resulting from calmer wind (Huber et al. 2012). In contrast, examining a heatwave in July 2015 in lake Mondsee in Austria, with phosphate below detection in mid-lake stations in summer (compared to 1 to 9 μg l^{-1} during spring circulation), insignificant changes to the total phytoplankton biomass were found. However, a shift in depth maxima during the heatwave from 11 to 16 m was found for the cyanophyte *Planktothrix rubescens* (Bergkemper and Weisse 2017; 2018). Such deep maxima can vary over time and may present a challenge for remote sensing with a shift to deeper depths by some species potentially being recorded as lower surface chlorophyll-a by satellite (Salmaso et al. 2018; Free et al. 2021b). In addition, such chlorophyll-a increases through heatwave driven stratification in deep lakes can be disrupted by storm events altering the stratification pattern and resulting in a rapid decline in concentration (Calderó-Pascual et al. 2020).

It is however indicated from this work and past studies that the strength of the response to heatwave and storm events is dependent on available nutrients and sufficient light, the latter being moderated by depth or stratification depth in deeper lakes. The greater tendency towards synchrony of temperature and chlorophyll-a with deeper lakes towards northerly latitudes indicates that light may be limiting in these situations. A heatwave event probably increases stratification, directly improves the light climate and causes the more rapid rise in chlorophyll-a in synchrony with temperature. Such lakes are typically colder and increasing temperatures towards the physiological optima for phytoplankton is likely to also play a role (Konopka and Brock 1978; Jöhnk

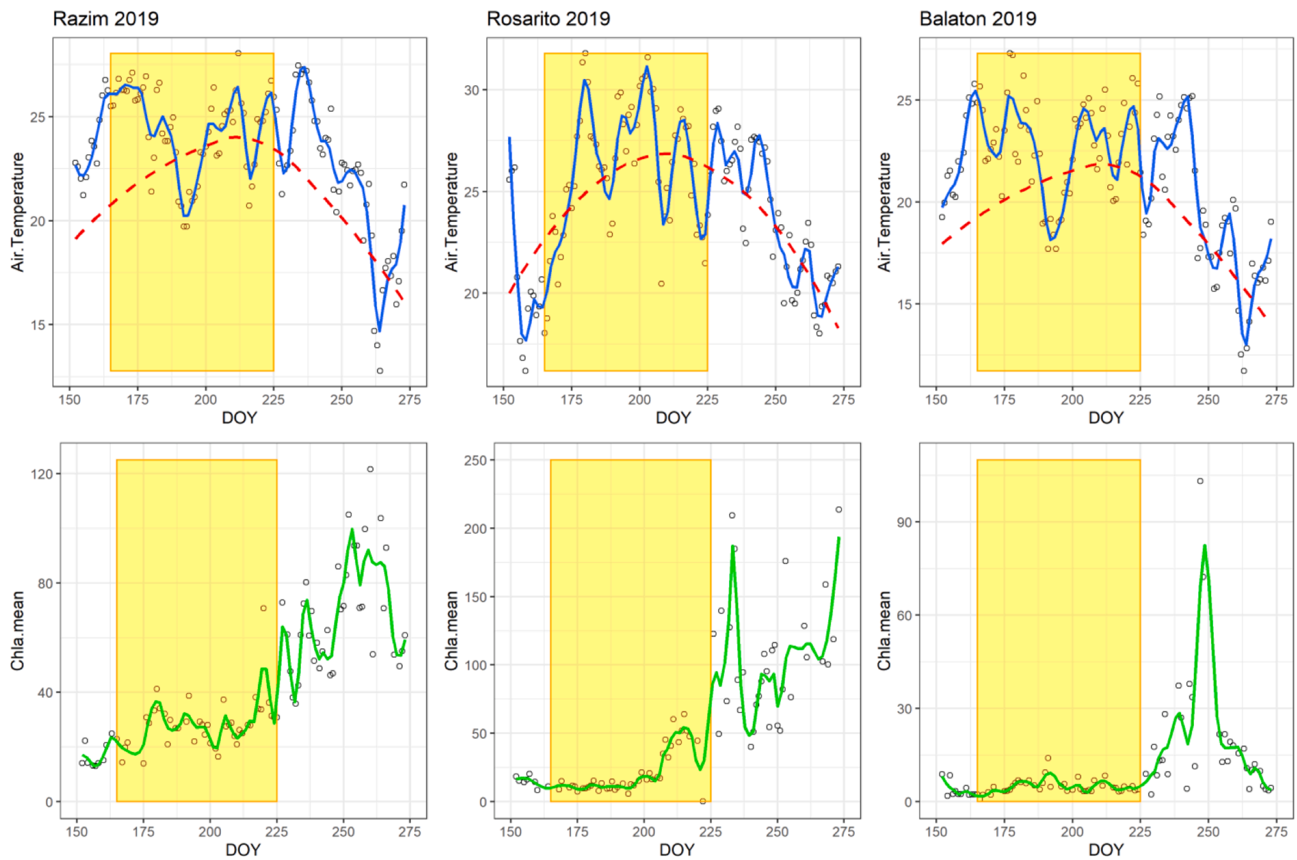

Fig. 5. Example of three shallow lakes (<7m) with large summer/autumn blooms outside the double heatwave event (Razim (Romania), Rosarito (Spain), Balaton (Hungary)). Top: Daily air temperature in 2019 (dots with blue smoothed lowess line) and average air temperature (°C) (1981–2010) (red dashed smoothed lowess line). Bottom: mean lake chlorophyll-a concentration (μg l^{-1}) in 2019 (dots with green smoothed lowess line). Yellow box highlights day of year (DOY) examined 165–225 (14 June–13 August). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

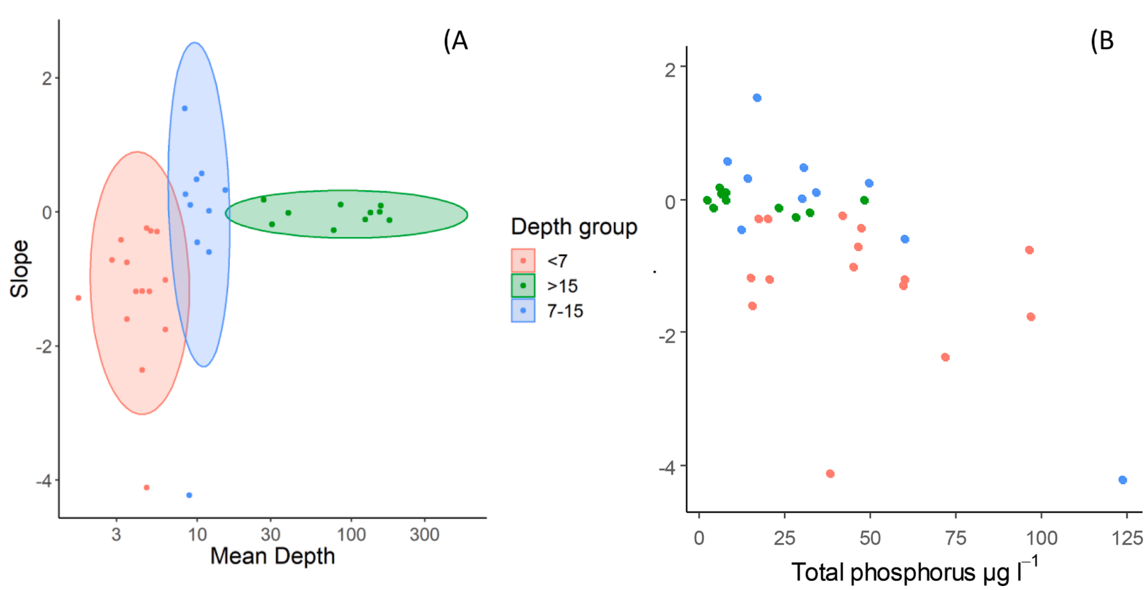

Fig. 6. Slope (from regression of temperature anomaly vs chlorophyll-a) vs log mean depth (panel A) and TP (panel B). Temperature anomaly calculated from daily 2019 temperature minus corresponding average for 1981 to 2010. Ellipses fitted by depth group. Lake Albufera (Spain) excluded as it had a large bloom in early June.

et al. 2008). Interestingly, a pan-European 230 lake study covering a heatwave in 2015 found the best relationship between temperature anomaly and increasing stratification strength for Boreal lakes, although Mediterranean lakes were less exposed to the heatwave (Donis et al. 2021). They also concluded that stratification strength and the light climate were most important in explaining chlorophyll-a during a summer heatwave, although stratification strength was interchangeable with depth to some extent. Total phosphorus concentration was not

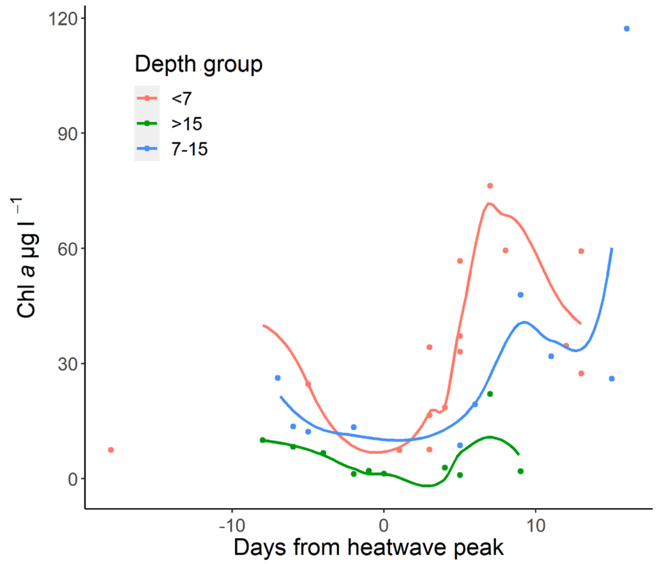

Fig. 7. Timing and concentration of peak chlorophyll-a with respect to the second 2019 heatwave. Lakes coloured and lowess smoother applied by mean depth group. Lake Albufera (Spain) excluded as it had a large bloom in early June.

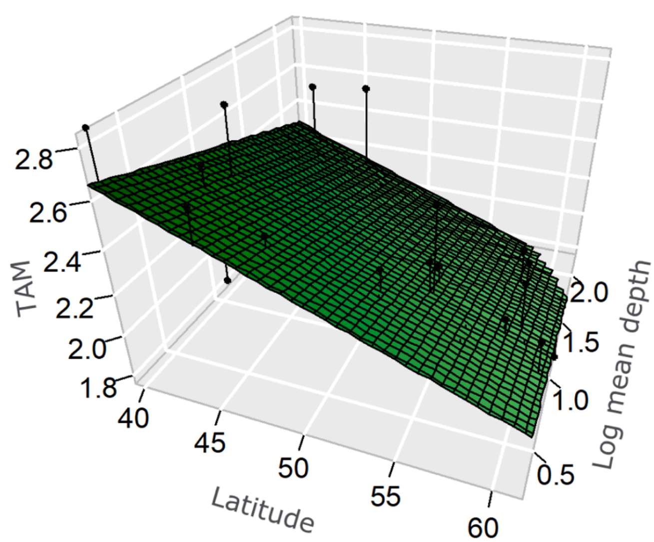

Fig. 8. Predicted TAM surface (Time Alignment Measurement on temperature and chlorophyll-a) from a multiple regression that included latitude and log mean depth. Measured values are black dots. Analysis performed over heatwave period (14 June–13 August). TAM of 0, indicates perfect temporal alignment while 3 indicates completely out of alignment.

significant which was concluded to be because the sample was mostly of eutrophic lakes (mean TP was 100 μg l^{-1}) and chlorophyll-a typically shows a linear response only up to 100 μg l^{-1} TP (Phillips et al. 2008; Donis et al. 2021). In addition, using Secchi disk depth to estimate light extinction may have complicated analysis as it may already represent components of the nutrient-chlorophyll-a relationship, especially for eutrophic lakes (Carlson 1977; Free et al. 2000).

4.2. The timing of the heatwave in the context of phytoplankton phenology

Some shallow lakes were also notable in having large algal blooms in late summer and early autumn coinciding with the drop in temperature reflecting changing season (Fig. 5). These large increases were three or more times that observed during the heatwave period. This underlines the importance of phenology in controlling the response of phytoplankton as summer/autumn is the season most typically associated with cyanobacterial blooms in temperate regions (Reynolds and Walsby 1975; Teubner et al. 2018). This can be confirmed for lake Trasimeno (Fig. 2) where weekly microscopic cyanobacteria counts show an increase after mid-August in 2019 matching the increase in satellite estimated chlorophyll-a (Free et al. 2022). However, information on taxonomic composition of the phytoplankton was not available for the other lakes to allow confirmation and given its importance in determining the response to heatwaves, future work should seek to incorporate this factor. If the timing of the heatwave was later in 2019, it may have resulted in larger blooms, for example the heatwave of 2003, occurred around mid-August and resulted in a *Microcystis* bloom (Jöhnk et al. 2008). The timing of the heatwave event and associated storm is therefore critical and should be specifically explored in data covering a longer time series. However, it has also been found that for a shallow mesotrophic Mediterranean lake, that a climate change driven increase in the duration of the warm season (above 20 °C) can lead to a reduction in such summer/autumn blooms. This probably occurs through earlier nutrient uptake by other taxa which can leave less for uptake by cyanobacteria in nutrient limited systems (Lepistö et al 2006; Free et al. 2022).

4.3. Response strength to temporally compounded heatwaves

It was anticipated that the double heatwave, being a temporally compounded event, might display a stronger response and impact on summer chlorophyll-a. However, evidence for this was not clear. For example, deep lakes Maggiore, Constance and Geneva appeared to show an increase in chlorophyll-a during the first heatwave event but not the second perhaps suggesting that nutrients may have been limiting as summer progressed. While for many lakes the chlorophyll-a levels following the second event were not markedly higher than the first. While for others, like lake Trasimeno, the chlorophyll-a continually increased in line with the low-pressure events that followed the heatwaves (Fig. 2). Here, the sequential cycle of several heatwaves and low-pressure events was found to punctuate the seasonal pattern of chlorophyll-a. In contrast for lake St. Augustin, a shallow eutrophic polymictic lake in Quebec, three successive heat events in 2012 each appeared to sequentially increase phytoplankton biomass but with a drop in biomass after the heatwaves, although the sampling frequency was bi-weekly to monthly reducing precision. Nonetheless, an analysis of historical pigment analysis found that 78 % of the variation in cyanophyte biomass could be explained by warming in this historically eutrophic lake (Bartosiewicz et al. 2019). In general, the response might be dependent on *in situ* conditions and to some extent be lake specific, thereby requiring analysis of a longer time series for each lake covering single and multiple event years. Analysis techniques for quantifying compound effects often require a sufficiently long dataset (Zscheischler et al. 2020). Recently a global statistical based analysis of 104 lakes found evidence to link compound lake heatwaves and high chlorophyll-a extremes but recommended further work to identify the drivers (Woolway et al. 2021b).

4.4. Temporal resolution and other factors

A different approach was applied in Lake Ontario where instead of heatwaves being directly examined, statistical extreme values in chlorophyll-a were examined in the context of antecedent weather. A higher number of hot days, above 27 °C, were found to precede extreme chlorophyll-a values. In addition higher rainfall in the three days preceding sampling was also correlated with higher chlorophyll-a, but explained only a minor percentage of the variation in a random forest model (Blagrave et al. 2022). In some regard, the conclusions that are drawn are influenced by the temporal resolution of sampling available.

While our study used data at relatively high frequency and drew distinctions between immediate and delayed responses to heatwaves, it is also the case that at a broader temporal scale, such as weekly or monthly, we would also have concluded chlorophyll-a peaks were associated with heatwaves. Essentially, with distinctions of timing aside, past work and this study show that if a heatwave promotes stratification to improve the light climate and nutrients are sufficient, chlorophyll-a will show an increase over the broad period from heatwave inception to dissipation. More studies at high frequency and *in situ* are required to understand the different processes across lake types and to enable a comparison with our study.

There are many other factors missing from the current study that could also help understand the variation in the chlorophyll-a response to heatwaves. For example, residence time can be important as significant storm events and flushing can suppress blooms in shallow lakes, whereas less rainfall and a lower lake water level in shallow lakes has been postulated to improve the light climate and promote blooms (Havens et al. 2019). However, in certain circumstances, a significant lowering of lake level can trigger a shift to an alternative state. Lower lake levels resulting from the 2003 heatwave were likely to have increased light levels resulting in a rapid spread of benthic macrophytes (Charophytes) with lower nutrients and suppressed phytoplankton peaks in Lake Scuro, Italy (Bertani et al. 2016). Another factor commonly included in *in situ* studies is information on stratification dynamics which has proved useful in understanding the mechanisms behind increases in chlorophyll-a during a heatwave and also its decline with storm events in deep lakes (Calderó-Pascual et al. 2020). Future studies could attempt to fill this gap by modelling stratification dynamics, for example using the FLake model (Mironov 2008). This should also allow a better understanding of how low-pressure systems or storms can impact on the chlorophyll-a dynamics, which were only inferred in this study from rapidly declining air temperatures. While storms can have a strict metrological definition, here we applied the term in a looser context to identify a sudden change in weather that has potential to effect change in the lake (Jennings et al. 2012; Stockwell et al. 2020). Detailed high frequency information on nutrient dynamics would also have been useful in interpreting the change in chlorophyll-a over the period of the two heatwaves. Finally, chlorophyll-a itself is only a limited indicator of how heatwaves may be changing lake ecosystems. Ideally information on phytoplankton and zooplankton species composition could be gathered to allow interpretation on how the community structure and their interactions, including predation, change in response to heatwaves. Heatwave dissipation by storms has been shown to cause rapid changes to the zooplankton community (Calderó-Pascual et al. 2020) and in extreme situations following a shift to a macrophyte driven state after the 2003 heatwave, cause a long lasting alteration to zooplankton communities (Bertani et al. 2016).

4.5. Role of satellite data, limitations and future direction

The dataset from the Lakes CCI project has the benefit of providing synoptic data globally at reasonably high temporal frequency over a long period of time using consistent methodology. The utilization of this dataset and particularly its frequency and coverage allowed the provision of one of the first studies into how lakes respond to compounded heatwave events at European level and underlined the key role of typological and trophic state parameters. This study and others illustrate that open access satellite data is increasingly becoming attractive for incorporation into local and regional monitoring programs for water quality and management (Toming et al. 2016; Bresciani et al. 2020; Topp et al. 2020). Comparing it with the effort required for ecological assessment (excluding fish), replicating this study *in situ* (June-September) to collect 2581 samples from the 36 lakes would take at least 373 working weeks. As heatwaves are forecast to occur with high frequency and given the EU commitment to the Copernicus programme it would be possible to plan large scale experiments certain of the contribution from satellite imagery. In addition, much more can be gained by extending a retrospective analysis using the Lakes_cci dataset, set to expand to 2000 lakes in 2022 (Crétaux et al. 2020). Further work is urgently required as current knowledge on the effects of extreme climate events on lakes is limited despite projected changes (Jeppesen et al. 2021b).

The integration of satellite-based data sets with detailed *in situ* high frequency data, especially on nutrient concentrations and stratification, represent a way forward in understanding phytoplankton dynamics during heatwave events. It would also clearly help in determining the phytoplankton bloom frequency in lakes – an identified gap in water policy at EU level (Poikane et al. 2015). Examining the chlorophyll-a response via regression against the temperature anomaly is a somewhat simple approach but was supported by two other approaches looking at the degree of synchrony (TAM) and peak distance from the heatwave event. Ideally, individual lake models should be built incorporating the time component but again a lot of the potential explanatory variables would have required *in situ* measurement at high frequency. Key to future analysis would be the need to track duration and movement of heatwaves and high-pressure areas as they influence the pathway of low-pressure systems, perhaps placing some lakes in the pathway of storms and high precipitation events (Lenggenhager and Martius 2019; Kautz et al. 2022).

5. Conclusions

In conclusion, the timing and magnitude of the response to the heatwave events depends on lake depth and nutrients. Deeper lakes respond sooner probably because of higher temperatures leading to stronger stratification thereby improving the light climate but with the response strength dependent on nutrient status. This was supported by lakes at higher latitudes, typically colder, showing greater synchrony between air temperature and chlorophyll-a. In contrast, shallower lakes, not typically light limited, and lakes at lower latitudes showed more asynchrony – with a greater response after the heatwave event probably as a result of internal and external loading. The phenology of the phytoplankton relative to the heatwave event is likely to be of key importance as several shallow lakes had much larger blooms outside of the heatwave period during the late summer and early autumn. Using remote sensing to derive estimates of chlorophyll-a as an indicator of phytoplankton abundance is the most feasible method of providing key data that is both at high frequency and synoptic – capable of covering large scale weather events at continental scale.

CRediT authorship contribution statement

Gary Free: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Mariano Bresciani:** Conceptualization, Writing – original draft, Writing – review & editing. **Monica Pinardi:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Stefan Simis:** Data curation, Funding acquisition, Methodology, Writing – original draft, Writing – review & editing. **Xiaohan Liu:** Data curation, Methodology, Writing – original draft, Writing – review & editing. **Clément Albergel:** Writing – original draft, Writing – review & editing. **Claudia Giardino:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data available online as open data. Please see: https://climate.esa.int/en/projects/lakes/about/

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109217.

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