Long-term trend of heat waves and potential effects on phytoplankton blooms in Lake Qiandaohu, a key drinking water reservoir

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Abstract

Global warming is increasing the frequency and duration of heat waves, which is defined as when air temperature exceeds a threshold for more than specific consecutive days. Ecosystem around the globe will be impaired by heat waves just like the exposures to dangerously high temperatures as a public health threat to human. However, the knowledge of the response of lake and reservoir ecosystem to heat waves is largely unknown although it has been argued that climate warming may increase the incidence of harmful algal blooms. We examined the long-term trend of heat waves and how the variability of phytoplankton biomass responds to lake heat waves on a deep reservoir (Lake Qiandaohu). Long-term (1980–2020) meteorological observation in the lake watershed showed a significant warming trend of 0.36 °C per decade for the yearly average of daily average air temperature and the yearly average of daily maximum air temperature of 18.32 °C was observed in 2016. Meanwhile, a significant increasing number of heat wave events lasting longer was observed, and Lake Qiandaohu suffered an unusually severe lake heat wave in summer 2016. Significant correlations were found between the yearly average of daily maximum air temperature and heat days, heat wave events, and heat wave days. Nuisance phytoplankton bloom was found in Lake Qiandaohu by high frequency observation and remote sensing monitoring in summer 2016. Remote sensing estimation from two Landsat 8 Operational Land Imager (OLI) images showed that the average chlorophyll *a* (Chl*a*) was $7.45 \pm 4.89 \mu\text{g/L}$ on July 18 before heat wave and $18.96 \pm 0.98 \mu\text{g/L}$ on August 19 during the heat wave. Two heat wave events lasting from July 20 to August 2 and August 11 to 26 with average surface water temperature of 29.93 and 31.99 °C promoted two marked phytoplankton blooms with average Chl*a* concentrations of 11.75 ± 4.08 and $10.53 \pm 1.65 \mu\text{g/L}$ in the central lake region, respectively, as evidenced by high-frequency buoy data. These findings suggest that heat waves are likely to yield an increased threat of harmful algal bloom in freshwater ecosystems. With lake heat waves projected to increase in frequency, duration, and spatial extent with global climate change, more studies are needed to improve our understanding of lake heat waves and their potential effects on the species, communities, frequency of phytoplankton bloom, and also help providing advanced schemes of water quality management.

Keywords Heat waves · Lake Qiandaohu · Phytoplankton bloom · High frequency · Remote sensing

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Introduction

Despite the COVID-19 lockdown, atmospheric concentrations of greenhouse gases continued to rise according to the interim report on the state of global climate in 2020 issued by the World Meteorological Organization (WMO). Therefore, climate change continued its relentless march in 2020, which is on track to be one of the three warmest years on record. The 2011–2020 will be the warmest decade on record, with the warmest 6 years all being since 2015 (<https://public.wmo.int/en/media/press-release/2020-was-one-of-three-warmest-years-record>). Parallel to further projected increases in global average air temperature, long-term observation, climate models, and physical reasoning indicate an

increase in the frequency and severity of many extreme climate events including heat waves, extreme rainfall, and hurricane (Coumou and Rahmstorf 2012). Heat waves is defined as when air temperature exceeds a threshold for more than a specific consecutive days (You et al. 2016). Several pieces of evidence from observation and modeling exemplify that climate warming has led to an increase in heat wave occurrence in terms of frequency and duration (Lopez et al. 2018; Mazdiyasi and AghaKouchak 2015; Rahmstorf and Coumou 2011). For example, the 2003 European heat waves as the hottest summer over the past 500 years, the exceptionally warm summer of 2010 in eastern Europe and large parts of Russia, and the 2013 summer heat waves in eastern China were widely reported (Coumou and Rahmstorf 2012; Garrahou et al. 2009; Matsueda 2011; Wang et al. 2017).

In addition to more frequent and more intense heat waves over land, climate change is leading thermal extremes at the water surface and column. Significant increases were observed in marine heat waves over the past century with the global average increase frequency, duration, and yearly heat waves days of 34%, 17%, and 54%, respectively, from 1925 to 2016 (Oliver et al. 2018). Spatial distribution, temporal trends, physical attributes, and biological impacts across different marine heat waves have been extensively examined (Di Lorenzo and Mantua 2016; Frolicher et al. 2018; Oliver et al. 2018; Smale et al. 2019). Although there are some studies about the effects of heat waves on lake and reservoir (Jankowski et al. 2006; Jöhnk et al. 2008; Li et al. 2017; Urrutia-Cordero et al. 2020), we know much less about heat waves in lake ecosystems and how they will change within a warming world in comparison to marine heat wave. Recently, lake heat waves similar to marine heat waves has been defined and changes of heat waves in the lake for hundreds of lakes worldwide from 1901 to 2009 using satellite observations and a numerical model have been investigated (Woolway et al. 2021). The results showed that lake heat waves will become hotter and last longer by the end of the twenty-first century under the continuing climate warming.

Heat waves have many disastrous and long-term lasting effects on human activities and natural ecosystems causing socio-environmental consequences worldwide and major biodiversity loss (Coumou and Rahmstorf 2012; Smale et al. 2019). For example, heat waves are associated with increased levels of human morbidity and mortality, and will be further strengthened by urban heat island effects and rapid urbanization (Conti et al. 2005; Fischer and Schar 2010; Mazdiyasi et al. 2017; Tan et al. 2010). Marine heat waves promote harmful algal bloom, threaten global biodiversity, and disrupt the provision of ecological goods and services (Hayashida et al. 2020; Roberts et al. 2019; Smale et al. 2019). Much attention has been given to climate change and freshwater ecosystem response especially increasing harmful algal blooms (HABs) with climate warming (Kosten et al. 2012; Michalak et al. 2013; Paerl and Huisman 2008; Posch et al. 2012). There are a few

studies linking heat waves, lake thermal stratification, and phytoplankton response (Jankowski et al. 2006; Jöhnk et al. 2008). However, the knowledge of the response of lake and reservoir ecosystem to heat waves is largely unknown and few direct evidence is reported to link heat waves and phytoplankton bloom although it has been argued that climate warming may increase the incidence of HABs.

In recent decades, heat waves are observed and projected to be more frequent, long-lasting, and widespread in the twenty-first century over China (Sun et al. 2014; Wang et al. 2017). An extremely dry and heat days were recorded in Qiantang River catchment and severe cyanobacterial bloom was found along the Qiantang River in 2016 (Guo et al. 2018) (Fig. 1). Therefore, we focused on Lake Qiandaohu, a reservoir located in the upper reach of Qiantang River and our specific aims of this study are as follows: (1) analyze long-term climate warming and heat wave occurrence characteristics; (2) characterize heat waves and phytoplankton biomass temporal–spatial pattern in 2016; and (3) examine the causality between heat waves and phytoplankton bloom to elucidate the potential effects of heat waves. We hypothesized that the occurrence of severe phytoplankton bloom in Lake Qiandaohu in 2016 was largely driven by atmospheric heat waves. We tested the assumption based on long-term air temperature observation, high frequency buoy- and satellite-monitored phytoplankton biomass.

Material and methods

Study region and sites

Lake Qiandaohu (29°22′–29°50′N, 118°36′–119°14′E) (meaning more than 1000 islands in Chinese) is a large reservoir built in 1959. Lake Qiandaohu has a water area of 580 km² when the normal water storage water level is 108 m, a mean depth of 31 m, a maximum depth of 100 m, a water volume of 178.6×10⁸ m³, and a watershed area of 10,480 km² (Zhang et al. 2015). Lake Qiandaohu is an important drinking water source for millions of people in Hangzhou (the capital of Zhejiang Province) and Jiaxing, and the largest strategic water source of the Yangtze River Delta. More than 2.0×10⁹ m³ water per year is transported to Hangzhou and Jiaxing through Lake Qiandaohu Water Diversion Project since 2020. Under the dual pressure of climate change and human activities, Lake Qiandaohu faces nutrient increase, Secchi disc depth decrease, phytoplankton bloom appearance, and water quality deterioration risk, which threaten drinking water supply safety (Li et al. 2020; Zhang et al. 2015; Zhang et al. 2020).

Meteorological data and heat wave

To characterize long-term trend of climate warming and heat waves in the lake watershed, the daily minimum, average, and

Fig. 1 Distribution of 6 meteorological stations including Hangzhou, Ningguo, Tunxi, Yushan, Jinhua, and Chun'an (a), 2 high frequency observation stations located in the main tributary of Xin'anjiang

(Nanfu) and reservoir area (Lake Center) (b), in situ high frequency buoy photo (c, d), location of Lake Qiandaohu in China (e), and phytoplankton bloom along River Xin'anjiang (f)

maximum air temperature from 1980 to 2020 from the China meteorological data sharing service system (<http://cdc.cma.gov.cn/home.do>) was used. In addition to Chun'an meteorological station (29°37'N, 119°01'E, 171.4 m) located in Lake Qiandaohu, other five closest meteorological stations—Ningguo (30°37'N, 118°59.0'E, 87.3 m), Hangzhou (30°14'N, 120°10'E, 41.7 m), Tunxi (29°43'N, 118°17'E, 12.7m), Yushan (28°41'N, 118°15'E, 116.3 m), and Jinhua (29°07'N, 119°39'E, 62.6 m)—were chosen, which were all within a radius of 80 km from the lake (Fig. 1a, squares). From the daily air temperature data, we calculated the yearly average values for each of the six meteorological stations. These data showed that the temperature data of six stations were characteristic of the region.

Many methods and thresholds were used to define and characterize heat waves including a fixed percentile of the temperature distribution or a fixed absolute value of temperature (You et al. 2016). Here, we used the Chinese Meteorological Administration's definition of a "heat day", which is defined as a day with daily maximum air temperature ≥ 35 °C, which was widely used to examine the patterns, trends, and occurrences of heat waves on regional and global scales (Huang et al. 2010; You et al. 2016). We defined a heat wave event as a period with at least three consecutive "heat day" (Huang et al. 2010). To fully characterize the frequency and duration of heat waves, we calculated heat days, starting

day of heat, heat wave events, starting day of heat waves, and heat wave days.

Remote sensing estimation of phytoplankton biomass

Two high spatial resolution Landsat Operational Land Imager (OLI) Level-1 images prior to (July 18, 2016) and post (August 19, 2016) heat waves were acquired from <https://earthexplorer.usgs.gov/> to elucidate the effect of heat waves on phytoplankton bloom. The atmospheric correction method for Landsat OLI images in the current study was the dark spectrum fitting (DSF) algorithm (Vanhellemont 2019; Vanhellemont and Ruddick 2018) which embedded in ACOLITE, a simple and fast for Landsat (5/7/8) and Sentinel-2 (A/B) imagery for coastal and inland water applications. DSF algorithm estimates the atmospheric path reflectance using two assumptions that the atmosphere is homogeneous over a certain extent and the scene contains pixels with the diffuse sky reflectance equal to 0 in at least one of the sensor band (Vanhellemont 2019). The Landsat-OLI-based chlorophyll *a* (Chl*a*) remote estimation model was developed in the previous study of Lake Qiandaohu exhibiting a high estimation precision of more than 70%, which has been extensively calibrated and validated using a large in situ dataset observed in Lake Qiandaohu and Landsat 8 OLI image (Li

et al. 2018). Specifically, the Chl a concentration distribution in Lake Qiandao was retrieved with the following equation (Li et al. 2018):

$$C_{Chl a} = 2.429 + 17.699 / \left(1 + \exp \left(-\frac{B3 + B4}{B2} - 2.325 \right) / 0.202 \right) \quad (1)$$

Where B2, B3, and B4 are the remote sensing reflectance of blue (450–510 nm), green (530–590 nm), and red (640–670) bands derived from Landsat 8 OLI image.

In order to reflect the anomalous Chl a concentration after heat waves in 2016, we include Chl a concentration remote sensing estimation in summer during 2013–2015 from the previous study (Li et al. 2018).

High-frequency observation of water temperature and phytoplankton biomass

High frequency buoy was deployed at Nanfu and Lake Center stations in Lake Qiandao (Fig. 1b–1d). The multiparameter sonde Yellow Springs Instrument (YSI) EXO2 instrument was attached to the buoy. EXO multiparameter sonde was the best-in-class platform to collect accurate field data in the natural environment. The sampling interval was 30 min at 3.0 m depth moored in the mixed layer to record long-term high frequency in situ observation data. Water temperature, dissolved oxygen, turbidity, Chl a , and chromophoric dissolved organic matter (CDOM) were simultaneously measured by the buoy instrument.

Statistic analyses

All statistical analyses including average values, standard deviations (SD), one-way ANOVA test, and linear fitting were performed using the Statistical Package for the Social Sciences software (SPSS 20, Chicago, IL). A significance level of $p \leq 0.05$ was reported as statistically significant. For simplicity and an easy comparison, long-term trends of air temperature and heat waves were determined using a linear regression analysis.

Results

Long-term trend of air temperature

The yearly averages of daily minimum, average, and maximum air temperature increased significantly over the last few decades at the meteorological Chun'an station during 1980–2020, with a linear slope of 0.42, 0.36, and 0.37 °C per decade

($p < 0.001$), respectively (Fig. 2). In comparison, the linear slope of minimum air temperature is markedly higher than that of maximum air temperature. Despite the broad global coherence in minimum and maximum air temperature increase, both trends can often diverge considerably showing a higher nighttime warming rate and decreasing air temperature difference between day and night. Meanwhile, overall significant warming results were similar for other five stations around Lake Qiandao (Table 1). However, the warming slopes of daily minimum, average, and maximum air temperature were slightly different for the six stations. All these results clearly demonstrated a rapid climate warming in Lake Qiandao.

Long-term trend of heat waves

Table 2 shows the long-term trend of heat day and heat wave event at six meteorological stations around Lake Qiandao by linear fitting. Overall, heat days, heat wave events, and heat wave days have significantly increased for all six stations. However, starting day of heat and starting day of heat waves have slightly advanced but not significantly for some stations. Therefore, heat wave events are becoming more frequent and commenced slightly earlier. In comparison, the frequency and duration of heat waves of three prefecture level cities (Hangzhou, Jinhua, and Tunxi) are stronger than those of three county level cities (Chun'an, Ningguo, and Yushan) (Table 2), which can be partially attributed to urban heat island effect of large city. We further focused on Chun'an meteorological station located in Lake Qiandao and found that significant correlations were observed between the yearly averages of daily maximum air temperature and heat days, heat wave event, and heat wave days ($p < 0.001$) (Fig. 3), indicating an increasing heat waves with climate warming.

Heat waves in 2016

There are 43 heat days and 37 heat waves days for Chun'an station in 2016 with the average daily maximum air temperature of 36.9 °C and 37.3 °C, respectively. The 37 heat waves days in 2016 ranks 3 during 1980–2020, which is less than 43 days in 1994 and 47 days in 2003. The summer of 2003 was unusually hot across much of Asia, and Shanghai recorded the hottest summer in over 50 years (Huang et al. 2010; Tan et al. 2004). Meanwhile, an extended heat wave resulted in above average air temperatures throughout Europe in July and August 2003 (Conti et al. 2005; Garrabou et al. 2009; Jankowski et al. 2006). The hottest day of the heat waves occurred on July 25, 29, and August 19 in 2016 with the same highest daily maximum air temperature of 39.3 °C. Four heat wave events are recorded in 2016 with two very long heat waves events lasting from July 20 to August 2, and from August 11 to 26, respectively (Fig. 4). In addition,

Fig. 2 Long-term (1980–2020) trend of yearly averages of daily minimum (a), average (b), and maximum (c) air temperature at the Chun'an meteorological station in the Lake Qiandaohu watershed. The red solid line represents the linear fitting. The light and dark red shaded area is the confidence band and prediction band of 95% curve confidence.

Fig. 2 shows the yearly average of daily average air temperature of 18.32 °C in 2016, which is the hottest year from 1980 to 2020, which is markedly higher than 17.87 °C in 2003 with the hottest summer. Therefore, heat waves in 2016 are very representative and typical.

Causality between heat waves and phytoplankton bloom

High frequency observation at Nanfu and Lake Center stations from July to September showed two marked phytoplankton

Table 1 Long-term trend of yearly averages of daily minimum, average, and maximum air temperature for six meteorological station in the Lake Qiandaohu watershed by linear fitting

Station	Parameters	Linear fitting	Determination coefficient (r^2)	Significance level (p)
Chun'an	Minimum air temperature	$y=0.042x-69.74$	0.65	0.000
	Mean air temperature	$y=0.036x-54.29$	0.60	0.000
	Maximum air temperature	$y=0.037x-51.17$	0.52	0.000
Ningguo	Minimum air temperature	$y=0.043x-74.42$	0.61	0.000
	Mean air temperature	$y=0.045x-73.44$	0.69	0.000
	Maximum air temperature	$y=0.049x-75.71$	0.60	0.000
Hangzhou	Minimum air temperature	$y=0.055x-95.45$	0.74	0.000
	Mean air temperature	$y=0.057x-96.73$	0.75	0.000
	Maximum air temperature	$y=0.061x-99.71$	0.71	0.000
Tunxi	Minimum air temperature	$y=0.046x-79.03$	0.69	0.000
	Mean air temperature	$y=0.048x-78.16$	0.77	0.000
	Maximum air temperature	$y=0.051x-80.28$	0.65	0.000
Jinhua	Minimum air temperature	$y=0.062x-108.56$	0.81	0.000
	Mean air temperature	$y=0.057x-95.94$	0.78	0.000
	Maximum air temperature	$y=0.058x-92.90$	0.69	0.000
Yushan	Minimum air temperature	$y=0.045x-76.58$	0.70	0.000
	Mean air temperature	$y=0.044x-70.46$	0.75	0.000
	Maximum air temperature	$y=0.052x-81.90$	0.66	0.000

Table 2 Long-term trend of heat days, starting day of heat, heat wave event, starting day of heat waves, and heat wave days at six meteorological stations around Lake Qiandaohu by linear fitting

Station	Parameters	Linear fitting	Determination coefficient (r^2)	Significance level (p)
Chun'an	Heat days	$y=0.299x-571.04$	0.094	0.050
	Starting day of heat	$y=-0.023x+216.52$	0.000	0.940
	Heat wave event	$y=0.070x-135.59$	0.272	0.000
	Starting day of heat waves	$y=-0.130x+450.59$	0.012	0.459
	Heat wave days	$y=0.328x-633.22$	0.119	0.027
Ningguo	Heat days	$y=0.358x-690.56$	0.164	0.009
	Starting day of heat	$y=-0.119x+396.06$	0.003	0.740
	Heat wave event	$y=0.051x-99.76$	0.163	0.009
	Starting day of heat waves	$y=-0.127x+442.22$	0.008	0.590
	Heat wave days	$y=0.315x-610.71$	0.138	0.017
Hangzhou	Heat days	$y=0.602x-1175.03$	0.303	0.000
	Starting day of heat	$y=-0.300x+764.80$	0.021	0.360
	Heat wave event	$y=0.088x-172.69$	0.435	0.000
	Starting day of heat waves	$y=-0.402x+989.23$	0.073	0.088
	Heat wave days	$y=0.580x-1136.16$	0.301	0.000
Tunxi	Heat days	$y=0.693x-1358.75$	0.347	0.000
	Starting day of heat	$y=-1.046x+2260.86$	0.175	0.006
	Heat wave event	$y=0.086x-168.24$	0.258	0.001
	Starting day of heat waves	$y=-0.326x+840.59$	0.064	0.132
	Heat wave days	$y=0.622x-1221.76$	0.322	0.000
Jinhua	Heat days	$y=0.657x-1277.56$	0.351	0.000
	Starting day of heat	$y=-0.447x+1056.17$	0.059	0.127
	Heat wave event	$y=0.091x-178.03$	0.317	0.000
	Starting day of heat waves	$y=-0.452x+1084.54$	0.139	0.016
	Heat wave days	$y=0.640x-1249.59$	0.321	0.000
Yushan	Heat days	$y=0.651x-1264.85$	0.295	0.000
	Starting day of heat	$y=-0.528x+1219.84$	0.082	0.069
	Heat wave event	$y=0.090x-175.03$	0.300	0.000
	Starting day of heat waves	$y=-0.411x+1002.96$	0.122	0.027
	Heat wave days	$y=0.614x-1197.59$	0.267	0.001

Fig. 3 Linear correlations between the yearly average of daily maximum air temperature and heat days, heat wave event, and heat wave days for Chun'an meteorological station from 1980 to 2020. The red solid line

represents the linear fitting. The light and dark red shaded area is the confidence band and prediction band of 95% curve confidence

Fig. 4 Daily maximum air temperature from January 1 to December 31, 2016, and the occurrence date of four heat waves events (Jun. 21–24, Jul. 20–Aug. 2, Aug. 11–26, Sep. 2–4) for the Chun'an meteorological station

blooms (Fig. 5). At Nanfu station, two Chl *a* peaks of 12.15 and 16.61 $\mu\text{g/L}$ were recorded on July 26 and August 15. Similarly, two Chl *a* peaks of 21.49 and 14.53 $\mu\text{g/L}$ were recorded on July 31 and August 20 at Lake Center station. Two Chl *a* peaks at the Lake Centre station both lagged 5 days behind those at the Nanfu station showing phytoplankton first appeared in inflowing river and the littoral zones. It is not surprising that two Chl *a* peaks coincided with the deployment of two heat wave events of July 20–August 2 and August 11–26 considering that heat waves may induce phytoplankton bloom (Jöhnk et al. 2008; Roberts et al. 2019). Overall, phytoplankton blooms lag behind 5–7 days of heat waves. Compared to 2017, marked Chl *a* peaks were recorded at Lake Center station in 2016 indicating anomalous phytoplankton bloom (Fig. 5b). The average Chl *a* concentration of 8.54 $\mu\text{g/L}$ in 2016 is significantly higher than 3.98 $\mu\text{g/L}$ in 2017 from July 1 to August 31 at Lake Center station (one-way ANOVA, $p < 0.001$). Further analysis showed that significant linear correlations were found between the daily Chl *a* concentration and the maximum air temperature for both Nanfu and Lake Center stations from July 1 to August 31 covering two heat wave events (Fig. 6).

We further investigated the spatial and temporal extent of this phytoplankton bloom by exploring two Landsat OLI

images before and after heat waves under clear sky. Since MODIS images have high temporal resolution monitoring the daily change of Chl *a* concentration but low spatial resolution larger than 250 m, we therefore examined Chl *a* concentration using Landsat OLI data. Spatial distributions of Chl *a* from two Landsat OLI images are shown in Fig. 7. Prior to the two heat wave events lasting more than 10 days on July 18, low Chl *a* concentration was recorded in addition to the north-west inflowing River Xin'anjiang with an average value of $7.45 \pm 4.89 \mu\text{g/L}$. After two heat wave events on August 19, higher Chl *a* concentration was recorded covering almost the entire Lake Qiandahu with an average value of $18.96 \pm 0.98 \mu\text{g/L}$. Although there is no defined threshold value for phytoplankton bloom, Chl *a* concentration greater than 10 $\mu\text{g/L}$ was considered to represent phytoplankton bloom conditions (White et al. 2014). By this metric, extensive phytoplankton blooms were apparent after two heat waves events which were coincident with the high frequency observation results. Actually, phytoplankton blooms were visible to the naked eye at the water surface observed during our field cruise (Fig. 1f). Spatially, Chl *a* concentration gradually decreased from the inflowing rivers to lake center and further to lake outlet (Fig. 7). In contrast, Chl *a* concentration was only 4.54 $\mu\text{g/L}$ (July 10, 2013), 4.30 $\mu\text{g/L}$ (August 11, 2013), 3.52 $\mu\text{g/L}$

Fig. 5 Daily variations of chlorophyll *a* concentration observed by high frequency buoy from July to September. (a): Nanfu station in 2016, (b): Lake Center station in 2016 and 2017. Marked chlorophyll *a* peaks on

Jul. 26 and Aug. 15 at Nanfu station, on Jul. 31 and Aug. 20 at Lake Centre station corresponding to two heat wave events during Jul. 20–Aug. 2 and Aug. 11–26.

Fig. 6 Linear correlations between daily chlorophyll *a* concentration observed by high frequency buoy and maximum air temperature from July 1 to August 31 in 2016 at Nanfu station (a) and Lake Center station

(June 11, 2014), 3.46 $\mu\text{g/L}$ (July 29, 2014), 3.79 $\mu\text{g/L}$ (August 1, 2015), and 2.75 $\mu\text{g/L}$ (September, 2015) in other normal years without the serious heat waves in summer (Li et al. 2018). These values were markedly lower than the threshold value of 10 $\mu\text{g/L}$ reflecting no marked phytoplankton bloom (Fig. 7).

Discussion

Increasing observed linkages between heat waves and phytoplankton bloom

Extreme climate events such as rainstorm and heat waves are exerting greater ecological and disaster effects than the average climate change due to an unprecedented and extensive increasing frequency and duration. Here we reported the increasing occurrence frequency of heat waves in Lake Qiandaohu and elucidate the effects of heat waves on phytoplankton dynamics combining satellite and high frequency observation. Our observation shows that heat wave events in the Lake Qiandaohu watershed in 2016 likely caused phytoplankton bloom in the lake. The development of phytoplankton bloom driven by summer heat waves has been confirmed by other studies (Bartosiewicz et al. 2019; Jöhnk et al. 2008). Lake experiment and model results showed that 2013 summer heat waves in Europe boosted the development of harmful cyanobacterial of Lake Nieuwe Meer, a deep hypertrophic lake in the Netherlands (Jöhnk et al. 2008). Similarly, summer heat waves fostered the development of high phytoplankton biomass in Lake St. Augustin, a shallow polymictic eutrophic lake in the USA (Bartosiewicz et al. 2019). Meanwhile, the U.S. West Coast experienced a massive HAB of *Pseudo-nitzschia* in 2015 that was associated with the 2014–16 Northeast Pacific marine heat wave (Ekstrom et al. 2020). Freshwater and marine results both showed summer heat

(b). The red solid line represents the linear fitting. The light and dark red shaded area is the confidence band and prediction band of 95% curve confidence

waves promoted phytoplankton bloom particularly applies to eutrophic and hypertrophic waters (Hayashida et al. 2020; Jöhnk et al. 2008). Weaker phytoplankton blooms are usually associated with summer heat waves in nutrient-poor waters, whereas stronger phytoplankton blooms are associated with summer heat waves in nutrient-rich waters. Increasing nutrients in the past decades in Lake Qiandaohu will inevitably boost the effects of summer heat waves on phytoplankton bloom (Da et al. 2019).

Direct and indirect effects of heat waves on phytoplankton bloom

Temperature is vital for the ecology of aquatic ecosystem, which have many direct effects on a wide range of ecological states and processes in lakes such as species distribution (Comte and Olden 2017), phytoplankton community (Deng et al. 2014), food web interactions (Tanentzap et al. 2020), and phenology (Shi et al. 2019; Urrutia-Cordero et al. 2020; Winder and Schindler 2004). For deep lakes and reservoirs, the phytoplankton biomass and community in the epilimnion were significantly affected by temperature. For shallow lake ecosystems, climate warming can indeed affect cyanobacterial dynamics at different life-history stages from benthic recruitment up to their pelagic dynamics (Urrutia-Cordero et al. 2020). In addition, high water temperatures during heat waves directly caused the change of phytoplankton community structure and boosted the development of harmful cyanobacterial blooms because many bloom-forming

Fig. 7 Spatial distribution of chlorophyll *a* concentration derived from Landsat OLI images in Lake Qiandaohu prior to (July 18) and post (August 19) heat waves in summer of 2016 and other years of 2013–2015. Marked increase of chlorophyll *a* concentration was observed from satellite data after two heat waves during Jul. 20–Aug. 2 and Aug. 11–26, 2016

cyanobacteria reached their maximal growth rates at relatively high water temperatures, often above 25 °C (Jöhnk et al. 2008; Paerl and Otten 2013). Previous studies showed that increasing water temperature is an important factor facilitating the intensification of HABs in inland waters (Huisman et al. 2018; Urrutia-Cordero et al. 2020). HABs have increased in frequency and spatial extent globally and could exert negative effects on aquatic ecosystems, fisheries, tourism, and human health with climate warming (Huisman et al. 2018).

In addition to the direct effects of increasing temperature induced by heat waves on phytoplankton growth rates and community succession, many other physical and chemical processes caused by heat waves indirectly affect the formation of phytoplankton bloom making the effects more complex than those on large plants and higher trophic levels. More stable thermal stratification during heat waves periods is a key driving mechanism for phytoplankton biomass anomalies. Heat waves often lead to a more stable stratification of the water column with less vertical mixing facilitating the accumulation of phytoplankton biomass and favoring the formation of dense surface phytoplankton blooms (Jankowski et al. 2006; Jöhnk et al. 2008). Additionally, reduced cloudiness and hence sunnier conditions during heat waves might enhance the growth rate of phytoplankton through an increased light availability indirectly affecting phytoplankton bloom (Jöhnk et al. 2008).

Implication for lake ecosystem

In addition to boost phytoplankton blooms, heat waves have many adverse effects on lake ecosystem. First, enhanced stratification associated with climate warming and heat waves resulted in the deoxygenation of bottom waters and oxygen losses (Bartosiewicz et al. 2019; Jane et al. 2021; Zhang et al. 2015). Thermal stratification affected the vertical distribution of dissolved oxygen and expanded the area of the hypoxic-anoxic zone. The incomplete mixing of the water from December 2016 to February 2017 because of summer heat waves and warm winter created the hypoxia hypolimnion from March to May 2017 (Liu et al. 2019). Second, phytoplankton blooms especially some HABs driven by heat waves may have direct toxic effects to kill zooplankton and fish. Results in Lake Peipsi showed summer heat waves of 1988 accompanied by a severe cyanobacterial bloom caused extensive fish kill, which indicated that heat waves in summer have profound detrimental effects on cool-water, autumn-spawning, short-lived fish such as vendace in shallow and polymictic lakes situated in the north temperate region (Kangur et al. 2020). Meanwhile, the large scale 2013 fish kill event in South Australia was attributed to an extensive marine heat wave which promoted algal blooms, including the harmful diatom *C. coarctatus* (Roberts et al. 2019). Third, heat waves often bring a greater risk of collapse of submerged plant communities and even drive massive losses of submerged aquatic vegetation (Arias-Ortiz et al. 2018; Kosten et al. 2009). For

example, 36% of Shark Bay's seagrass meadows were damaged following a marine heat wave in 2010/2011 (Arias-Ortiz et al. 2018). Water quality decrease, losses of carbon, and associated CO₂ emissions following degradation of submerged aquatic vegetation ecosystems have been documented previously (Zhang et al. 2017), which will threaten many ecological goods and services including drinking water provision and carbon sequestration. Therefore, understanding, predicting, and quantifying the response of lakes and reservoirs to heat waves are critical for decision-making and ecosystem management involving water resource management policies and to understand how ecosystems will respond.

Future research directions

This study analyzed the linkages between heat wave events and phytoplankton blooms based on the extensive field investigations. However, it is difficult to distinguish or quantify the contribution of heat waves and normal high temperatures to phytoplankton bloom in our study. Controlled experiment should be carried out to distinguish the differences of phytoplankton bloom caused by heat waves or normal high temperatures in our future study (Jeppesen et al. 2021a; Jeppesen et al. 2021b). There is a clear need to examine the driving mechanism and quantify the relative contribution of heat waves and nutrients in determining phytoplankton bloom response using mesocosm control experiment and numerical modeling because previous study showed that phytoplankton blooms are weaker driven by heat waves in nutrient-poor waters, whereas in nutrient-rich waters, the heatwave-induced algal blooms are more prominent (Hayashida et al. 2020; Jöhnk et al. 2008). In addition, more studies are needed to elucidate the combined effects of heat waves and phytoplankton bloom on zooplankton, fish, and even zoobenthos because climate warming and heat wave can alter many physical and chemical environment with direct or indirect effects on ecosystem structure and function (Garrahou et al. 2009; Jankowski et al. 2006). Actually, a wide range of ecological goods and services including the widespread loss of biogenic habitat, extensive cool-water fish kill fish death, depleted biodiversity, threat to drinking water, carbon sequestration decrease, and diminished socioeconomic value have been severely affected by heat waves (Bergkemper et al. 2018; Kangur et al. 2020; Smale et al. 2019). These services have substantial societal benefit, with hundreds of millions of people benefitting from lake and reservoir ecosystems. Therefore, managing and mitigating the deleterious effects of heat waves on the provision of ecosystem services is a major challenge in the future study.

Conclusions

We identified an increasing frequency and duration of heat waves in the Lake Qiandaohu watershed as a consequence of

climate warming, which will probably increase the risk of severe, pervasive, and long-lasting effects on aquatic organisms, especially on those with reduced mobility and high vulnerability. Lake Qiandaohu experienced unprecedented hottest year and heat wave events in 2016. Meanwhile, extensive phytoplankton blooms were observed along the Xin'anjiang River and Qiantang River. We exhibited that two long-lasting and strong heat wave events in 2016 caused marked phytoplankton blooms using high spatial resolution Chl_a remote sensing estimation from Landsat OLI satellite data and high temporal resolution Chl_a from high frequency buoy observation. Our findings of climate warming and increasing heat waves are important to understand the consequences of climate change on lake ecosystems and improve our management of lake water quality. However, the responses of aquatic organisms and ecosystems to heat waves can be variable and difficult to predict owing to species- and system-specific responses. More studies are needed to assess the response of aquatic organisms and ecosystems to an increasing occurrence of heat waves in the foreseeable future.

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Declarations

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