Science of the Total Environment 651 (2019) 614–624

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Thermal stratification dynamics in a large and deep subtropical reservoir revealed by high-frequency buoy data

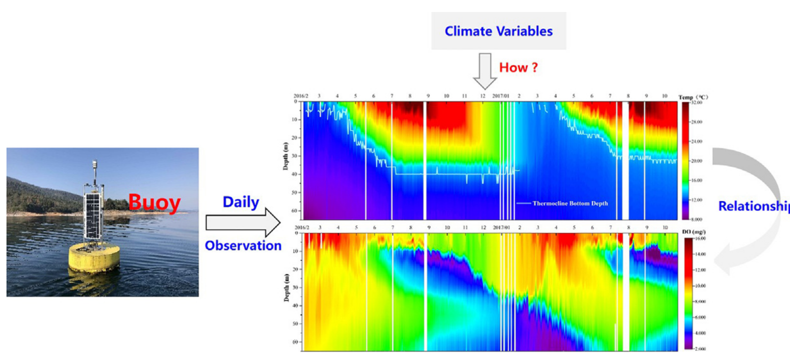
Miao Liu [a,b], Yunlin Zhang [a,b,*], Kun Shi [a,b], Guangwei Zhu [a,b], Zhixu Wu [c], Mingliang Liu [d], Yibo Zhang [a,b]

[a] Taihu Lake Laboratory Ecosystem Research Station, State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[b] University of Chinese Academy Science, Beijing 100049, China
[c] Chun'an Environmental Monitoring Station, Hangzhou 311700, China
[d] Institute of Environmental Protection Science, Hangzhou 310014, China

HIGHLIGHTS

- A consecutive 20-month high-frequency water-temperature profile was shown in a large subtropical reservoir.
- The thermal-stratification cycle was divided into formation, stationary and weakening periods.
- Thermal stratification affected the vertical profile of dissolved oxygen and expanded the area of the hypoxic-anoxic zone.
- The thermal stratification of Lake Qiandaohu will intensify with global warming.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 May 2018
Received in revised form 16 September 2018
Accepted 17 September 2018
Available online 18 September 2018

Editor: R Ludwig

Keywords:
Thermal structure
Lake Qiandaohu
Climate warming
Buoy

ABSTRACT

We measure the thermal stratification dynamics in Lake Qiandaohu, China, a deep subtropical reservoir, to better understand the mixing mechanism and its response to lake warming. A high-frequency monitoring buoy dataset from February 2016 to October 2017 is used to evaluate variations in the water temperature profile, Schmidt stability (SS) and thermocline parameters, such as the thermocline depth (TD), bottom depth (TB), thickness (TT), and strength (TS), and elucidate the potential effects of thermal stratification on the lake's ecosystem. High-frequency observation data demonstrate that the lake's thermal-stratification cycle can be divided into three stages: formation, stationary and weakening periods. Consequently, a significant positive correlation between the TB and TT during the formation period and a significant negative correlation between the TD and TT are found during the stationary and weakening periods. Additionally, strong positive correlations exist among the TS, TT and SS for all the data. Our data indicated that an increase in the air temperature caused the surface water temperature, TT, TS and SS to increase. Furthermore, 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 the high air temperature, which was 2.49 °C higher than the mean air temperature of 1966–2015 (6.44 °C), created the hypoxia hypolimnion from March to May 2017. Under the background of global warming, the thermal stratification of Lake Qiandaohu will likely intensify and further significantly affect the lake's ecosystem.

* Corresponding author.
E-mail address: ylzhang@niglas.ac.cn (Y. Zhang).

https://doi.org/10.1016/j.scitotenv.2018.09.215

1. Introduction

Lake thermal stratification refers to the uneven distribution of water temperature in vertical profiles, which is a basic and important physical process in lakes (Aeschbach-Hertig et al., 2007; Zhang et al., 2014). This process controls water mixing and convection, nutrient cycles and the vertical distribution of dissolved oxygen (DO) and particles and causes a variety of physical and chemical processes (Aparicio et al., 2017; Paerl et al., 2014; Zhang et al., 2015). The surface water is in close contact with air and is easily heated by solar radiation, where light is sufficient but nutrients are scarce. In contrast, the temperature of the bottom water is low and stable, and nutrients are rich but light is insufficient (MacIntyre et al., 1999). The thermocline layer (metalimnion) between the surface and bottom water is often observed as a region of sharp changes in water temperature that delineate an upper well-mixed region (epilimnion) from a relatively quiescent deep zone (hypolimnion). This vertical partition of the water column has significant implications for the availability of DO, nutrients, light and microbial substrates (Becker et al., 2009; Hao et al., 2012; Jankowski et al., 2006), alongside the vertical distribution, migration and metabolism of phytoplankton and zooplankton and organic-matter degradation (Becker et al., 2010; Chen et al., 2009).

Lakes are considered the sentinel of global climate change (Adrian et al., 2009), and the warming of lakes because of climate warming can change lakes' thermal-stratification properties (Arhonditsis et al., 2004; Coats et al., 2006; Oreilly et al., 2015). Thus, studying thermal stratification will help us understand the effects of global climate change on the ecological environments of lakes. On the other hand, changes in lake thermal stratification also affects the nutrient cycle, such as the formation of the nutricline, especially in the upper layers of water bodies (Cermeño et al., 2008), and promotes the eutrophication of lakes and harmful algal blooms (Posch et al., 2012; Wilhelm and Adrian, 2008). Therefore, understanding the process and formation mechanism of lake thermal stratification and clarifying its driving factors are also important for water-quality management in lakes (Zhang et al., 2014).

Generally, thermal stability and lake-thermocline parameters (e.g., thermocline depth and thickness) are commonly used to characterize lake thermal stratification. The thermal stability of lakes reflects the overall dynamic state of water in stratification periods (Idso, 1973; Read et al., 2011; Schmidt, 1928). Higher stability means less mixing and more intense stratification. In addition, the parameters of the thermocline focus on the response of lakes to changes in the lake heat balance and mixing mechanisms; in particular, the thermocline depth and thickness can indicate the characteristics of climate change (Stainsby et al., 2011). The thermal structure of lakes is influenced by the lake morphology (size and fetch), solar radiation, light penetration (transparency and diffuse attenuation coefficient), and climate factors (water temperature, wind speed, and precipitation) (Fee et al., 1996; Kraemer et al., 2015; Saros et al., 2016). The heat flux and light penetration are usually the most important driving factors for the seasonal and spatial variations in thermal structures in a specific lake (Einem and Granéli, 2010; Zhang et al., 2014). Transparency is a key factor that controls the thermal-stratification variations of lakes in middle and high latitudes, influencing the solar radiation that is absorbed in surface waters (Fee et al., 1996; Read and Rose, 2013; Saros et al., 2016). Moreover, chromophoric dissolved organic matter (CDOM) can affect the absorption of solar radiation and the water transparency, especially for humic waters (Flaim et al., 2016; Saros et al., 2016; Strock et al., 2017). For eutrophic lakes, chlorophyll-*a* (Chl-*a*) and the amount of phytoplankton restrict thermal stratification (Berger et al., 2010; Winder and Hunter, 2008). Furthermore, climate variables such as the air temperature have altered the properties of thermal structures and stratification regimes over recent decades in many areas of the world (Kraemer et al., 2015), and precipitation and wind influence the water quality, such as the transparency and material composition of lakes (Gaiser et al., 2009).

To date, the effects of climate warming on lake thermal stratification mainly involve the stratification duration, thermocline depth, thickness and thermal stability (Oreilly et al., 2015; Peeters and Livingstone, 2002; Stainsby et al., 2011; Wilhelm and Adrian, 2008). Most previous studies showed that climate warming will intensify thermal stratification, and long-term temperature rises and short-term extremely high temperatures will prolong the duration of lake thermal stratification (Austin and Colman, 2008; Michelutti et al., 2016), decrease the thermocline depth (Coats et al., 2006; Zhang et al., 2014) and increase the thermal stability (Hampton et al., 2008; Stainsby et al., 2011; Winder and Schindler, 2004). However, the effects of air temperature on the thermal stratification of lakes are different during different periods in one year because of the various environments and material compositions of lakes. The responses of different regions and types of lakes to global climate changes may not be the same; more observation data are required to elucidate the variations and mechanisms of thermal stratification.

Within the global lake-observation network, most studies on lake stratification have focused on large North American, northern European and Equatorial lakes (Austin and Colman, 2008; Coats et al., 2006; Hampton et al., 2008; Livingstone, 2003; O'Reilly et al., 2003), but limited studies have been conducted in China or Asia as a whole (Chen et al., 2009; Huang et al., 2017; Wang et al., 2012; Wen et al., 2016; Zhang et al., 2014). These regions are usually affected by the sea-land thermal contrast, and the temperature and rainfall are distinct under the influence of monsoons. These lakes are a significant component of the total lake area in the world; therefore, studies that cover different regions and explore the mechanisms of lake thermodynamics in mid-latitude subtropical regions and their responses to global warming are necessary. On the other hand, previous studies of thermal dynamics mainly used monthly, seasonal, annual and decadal data to describe the temporal variations in thermal stratification and its responses to climate change (Hampton et al., 2008; Livingstone, 2003; O'Reilly et al., 2003), which cannot adequately elucidate the hourly and daily cycle characteristics and driving mechanisms (Bruesewitz et al., 2015; Saros et al., 2016). With the rapid development of sensor techniques and high-frequency observations, the formation and weaknesses of thermal stratification are likely to be fully characterized and quantified by using minute, hourly and daily data from water-temperature profiles.

Therefore, this study uses consecutive 20-month high-frequency water-temperature-profile data from Lake Qiandaohu to (1) present the temporal variations in the temperature profiles, thermal stability and thermal stratification parameters at a daily scale and meticulously determine the stratification-cycle process; (2) analyze the driving factors of thermal stratification in different stratified periods; and (3) elucidate the potential environmental effects of stratification on lake ecosystems. The mechanisms and driving forces for the formation of thermal stratification in this study provide a theoretical basis for the future modeling of lake thermal stratification and responses to climate change with long-term seasonal data observations.

2. Data and methods

2.1. Study area

Lake Qiandaohu (29°22′–29°50′N, 118°36′–119°14′E) is located in western Zhejiang Province and southern Anhui Province, China (Fig. 1). The lake is a long, narrow reservoir that has many bays, and the greatest length and width of its bays are 150 km and 50 km, respectively (Zhang et al., 2014). Lake Qiandaohu has a water area of 580 km^2, an average depth of 30 m, a water volume of 178.4×10^8 m^3, and a basin area of 10,480 km^2 when the normal water storage level is 108 m. Lake Qiandaohu is stratified for most of the year, with only a short mixing period during winter, which is consistent with many similar subtropical or tropical reservoirs. The thermal-stratification response in Lake Qiandaohu to long-term climate change and it′s environmental effects