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3D hydrodynamic investigation of thermal regime in a large river-lake-floodplain system (Poyang Lake, China)

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ABSTRACT

Thermal regime and its response to meteorological and hydrological forcings play an important role in controlling water quality and ecosystem of lakes. Many large floodplain lakes are subjected to significant river-lake interactions and could benefit greatly from hydrodynamic modeling. The current work presents a first attempt to use a 3D hydrodynamic model and statistical methods to explore spatiotemporal variations and primary causal factors of thermal stability within a large river-lake-floodplain system (Poyang Lake, China). The hydrodynamic model successfully reproduced the lake hydrodynamics and thermal dynamics through a comparative analysis of field measurements. Simulation results revealed that the thermal stability of Poyang Lake exhibits similar spatial patterns between seasons; however, the lake is generally stratified during summer and early autumn. It is classified as partial mixed and full mixed during winter and spring. The thermal stratification may develop in the center area and eastern bay area of the lake, while the full mixing is likely to occur in the floodplains and the main flow channels. Statistics and simulations indicate that the air temperature, solar radiation and evaporation trigger a positive effect on the thermal stability of Poyang Lake, whereas a negative relationship is recognized due to the catchment river temperature. The responses of thermal stability to the meteorological and hydrological changes are much stronger in summer than other seasons, producing a significant seasonal thermal regime in the floodplain lake. Additionally, the dynamics in the lake water depth and associated hydrological regime are a major factor in maintaining the seasonal thermal stability of Poyang Lake. The findings of this study can support management of Poyang Lake as well as other similar floodplain lakes, by providing information on both water quality and ecosystem succession.

1. Introduction

Thermal regime characteristics, such as water temperature, thermal mixing and stratification, play an important role in controlling water quality (e.g., chemical and biological processes, vertical exchange of water-borne particles of various kinds), and ecosystem succession (e.g., cyanobacterial growth and dominance) of lakes and reservoirs (Wahl and Peeters, 2014; Wu et al., 2016; Barrett et al., 2018; Feng et al., 2018). Considerable attention to the impacts of rapid climate change and anthropogenic processes of the thermal regime has made headlines as politicians discuss global warming. However, climate change does affect heat and mass transport in many of the world's lakes (Wang et al., 2012; Kirillin and Shatwell, 2016).

Thermal stratification and mixing in lakes are driven by several factors ranging from lake morphometric characteristics (Kling, 1988; Hanna, 1990), to lake hydrological conditions (Martin and McCutcheon, 1999; Lawson and Anderson, 2007), through to meteorological and climatic forcings (Stainsby et al., 2011; Read et al., 2014; Wahl and Peeters, 2014). Lakes can be classified as stratified, partially stratified/mixed or vertically mixed, and the variability associated with stratification ranges from hours to decades and varies on global and regional scales (Read et al., 2011; Bertone et al., 2015). Most lakes are in climatic zones with strong shifts between dry and wet seasons; hence, seasonal thermal conditions are fundamental for all physical, chemical and biological processes in lakes (Boehrer and Schultze, 2008). Therefore, an improved understanding of thermal regimes is a key objective of limnology and can substantially aid in future assessment and management of the environmental state of lakes.

Thermal regime and its causal factors in lakes have been extensively examined using field measurements and hydrodynamic models.

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Previous investigation includes the field-based study of Chowdhury et al. (2015), who used a chain of fast-response temperature loggers to examine the stratification and mixing in Lake Simcoe (Canada). They found that the lake's mixing exhibits large spatial and temporal variability. Lawson and Anderson (2007) used water temperature profiles to investigate the thermal regime in Lake Elsinore (California). They concluded that thermal stability strongly depends upon variations in lake water level. Changes to the thermal stability of lakes such as shorter duration of ice-cover, earlier onset of stratification and an increase in the length of the stratified period have already been observed in some lakes in North America and Europe (e.g., Magnuson et al., 2000; Winder and Schindler, 2004; Wilhelm and Adrian, 2008; Stainsby et al., 2011).

Many previous studies have applied a vertical 1D hydrodynamic model to explore the thermal stability and associated external responses for several lakes (Danis et al., 2004; Herb and Stefan, 2005; Mackay, 2009; Read et al., 2011, 2014). Hydrodynamic investigations include the application of heat exchange equations by Tuan et al. (2009) to model the 1D thermal stratification in Shikinawa Lake (Japan). It was found that diurnal stratification is mainly affected by wind action, while thermal heating plays a minor role during strong wind events. In cases where the lake exhibits a complexity of lake bathymetry and a wide and continuous range of hydrodynamic variations, analyses based on 1D models can become complicated (Wahl and Peeters, 2014; Li et al., 2017a). Indeed, horizontal transport in such lakes may limit the accuracy of 1D models by assuming a vertical mixing process (Herb and Stefan, 2005; Wahl and Peeters, 2014). Therefore, 3D hydrodynamic models are convenient and useful tools to identify the spatiotemporal evolution of the lake thermal regime and its response to external forcings. Wang et al. (2012) investigated the effects of climate and hydrological conditions on the thermal stability of the Liuxihe Reservoir (China) using a 3D ELCOM hydrodynamic model, showing that water column stability is influenced by both natural factors and anthropogenic factors. Xue et al. (2015) developed a 3D FVCOM hydrodynamic model to explore the thermal response to meteorological forcings in Lake Superior (at the America-Canada border). They found that spatiotemporal variability of heat fluxes can have an important influence on the lake's 3D thermal structure. Arifin et al. (2016) used a 3D EFDC hydrodynamic model to simulate thermal behavior in Lake Ontario (covering an area along the America-Canada border). They concluded that the hydrodynamic model successfully reproduced the temperature profiles and thermal bar evolution. Additionally, Wu et al. (2016) used the 3D EFDC model to focus on the impact of thermal stability on pollutant transport in the Hongfeng Reservoir (China), showing that the spatiotemporal variations in stability are primarily affected by air temperature and water depth and, hence, control water age differences. These previous efforts to elucidate thermal regime have mainly focused on lakes that do not exhibit complex floodplain characteristic. Zhang et al. (2017) found that most floodplain lakes have considerable fluctuations in water level and often have highly variable hydrological and thermal dynamics. Floodplain lakes are generally large with many surrounding rivers, which serve as inlets and outlets, and constitute significant river-lake-floodplain systems (Zhang et al., 2018). The thermal regime of floodplain lakes quickly respond to the spatiotemporal variability of hydrological and meteorological conditions and are, therefore, prone to changes in the external environment (Townsend, 2006; Wiklund et al., 2010; Zhang et al., 2017). Such knowledge of large floodplain lakes have received little attention compared with deeper lake systems (Li et al., 2017b).

Poyang Lake is the largest freshwater lake in China (Shankman et al., 2006) and represents significant biodiversity and ecological values that are of interest to the international wetland system (Yang et al., 2018). Thus, Poyang Lake has become recognized as a significant floodplain system with complex river-lake interactions (Zhang et al., 2014; Li et al., 2015a), which leads to highly dynamic hydrological and thermal regimes (Li et al., 2017a,b). The natural fluctuations of the lake water level have attracted considerable public attention during the past decade (Hu et al., 2007; Zhang et al., 2012, 2014; Li et al., 2017a), due to climate change and human activities that have resulted in significantly detrimental ecological and economic outcomes (Mei et al., 2016). More importantly, steadily deteriorating water quality and rapid environmental degradation have already intensified (Cheng and Li, 2006) and may be impacted further by operation of the Three Gorges Dam and the proposed hydraulic dam located in the Yangtze River's upstream and the lake's downstream, respectively (Yang et al., 2016). Many studies have suggested that the floodplain Poyang Lake is vulnerable to hydrological alterations and thermal dynamics (Wu et al., 2014; Liu et al., 2016; Zhang et al., 2018). Therefore, knowledge of thermal regime behavior may have significant implications for water quality and nutrient exchange of the floodplain lake.

In previous studies of Poyang Lake, several 2D hydrodynamic models of the lake were constructed and used to investigate lake hydrodynamics and/or thermal dynamics (e.g., Lai et al., 2013, CHAM; Li et al., 2014, 2017b; Yao et al., 2018, MIKE 21; Wang et al., 2015, EFDC), mainly due to lack the information regarding the vertical thermal structures. For example, Li et al. (2017b) used the depth-averaged MIKE 21 model to examine the spatiotemporal behavior and primary causal factors of water surface temperature in Poyang Lake. They concluded that the water surface temperature exhibits strong spatial and temporal variability, and is mainly influenced by air temperature, solar radiation, wind speed and river temperature. However, the vertical processes of transport and mixing in these 2D hydrodynamic models have generally been oversimplified, based on the assumption that the shallow and wide characteristics of the lake do not have enough substance or change to be modeled (Li et al., 2014). In other words, the circulation pattern and the associated thermal stratification of the lake were neglected in previous 2D modeling studies. Recently, the thermal stratification and its causal factors have been of keen interest. Li et al. (2016b) investigated the thermal stratification and mixing of Poyang Lake using the depth profile measurements of water temperature. They found that the lake has isothermal mixed layers from the epilimnion to the hypolimnion. However, even though their results may reasonably represent the thermal conditions in the lake's main flow channels, the results did not apply to other regions of the lake. The work was, thus, incomplete because it only focused on the limited observation points in the main flow channels at specific sampling periods. This lack of sufficient records on environmental changes in floodplain lakes (Zhang et al., 2018), left information gaps regarding thermal stability and its responses in the floodplain of Poyang Lake.

Despite several previous studies into the thermal regime and its implications of Poyang Lake, this study is the first to use a 3D hydrodynamic model and, hence, provides the first attempt to examine thermal stability within a large floodplain lake system. Our specific objectives were (1) to construct and validate a 3D hydrodynamic model to simulate the thermodynamics of the lake, (2) to evaluate the spatiotemporal patterns of the thermal stability throughout the lake, and (3) to investigate the influence of primary external changes on thermal stability using statistical and hydrodynamic approaches.

2. Study area

Poyang Lake (28°4′-29°46′ N, 115°49′-116°46′ E) is an internationally recognized wetland system (Kanai et al., 2002) with a significant seasonal shift between dry and wet seasons. It is also the largest freshwater lake located at the south bank of the middle reaches of the Yangtze River (Fig. 1). Poyang Lake is one of the few lakes in China that remains naturally connected to its surrounding rivers (Zhang et al., 2014). According to statistics, the region's subtropical monsoon climate produces a mean annual precipitation and pan evaporation of 1485 mm/yr and 1428 mm/yr, respectively. Poyang Lake receives catchment runoffs from the Ganjiang (average = 2585 m^3/s), Fuhe (526 m^3/s), Xinjiang (744 m^3/s), Raohe (642 m^3/s), and Xiushui