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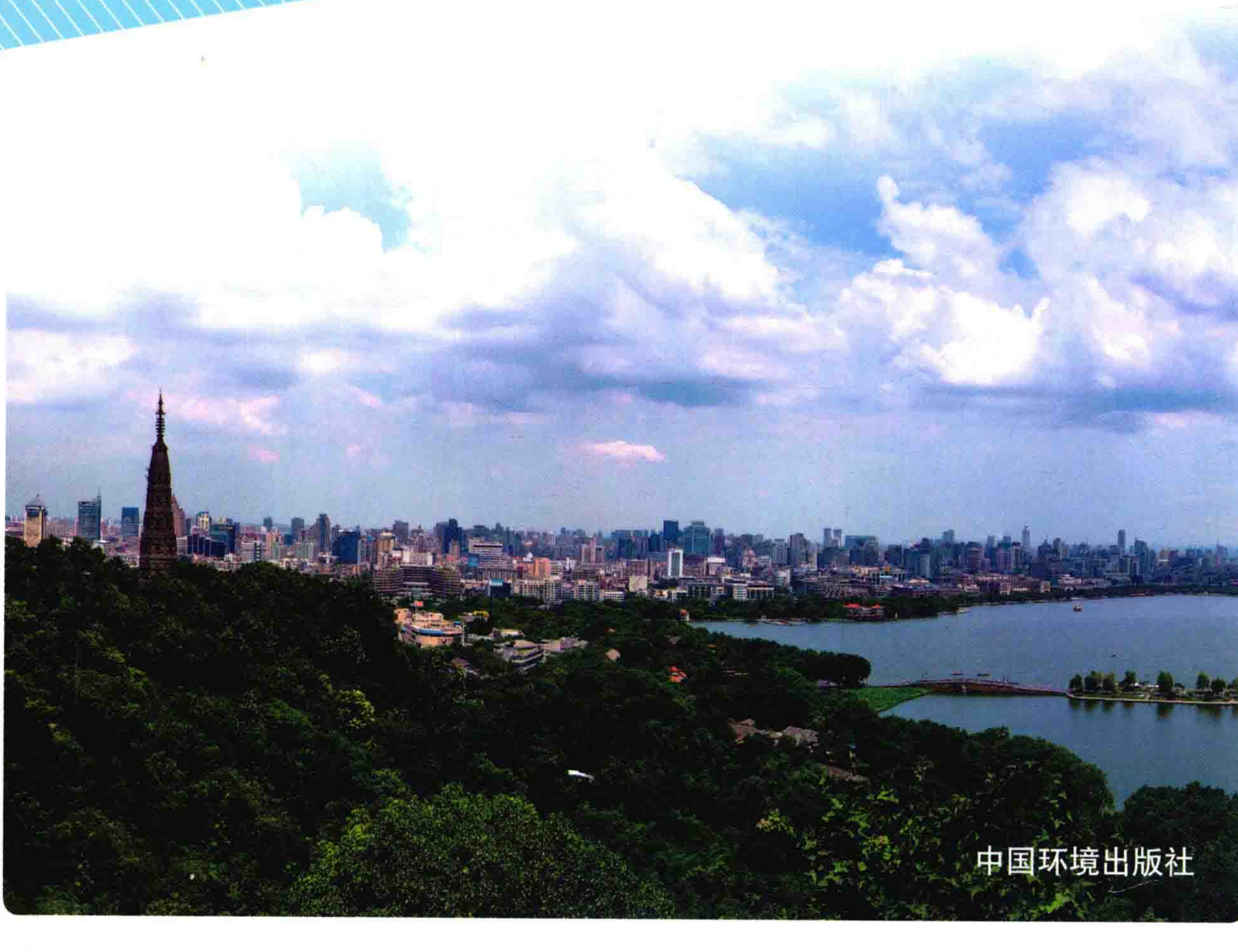
（2010—2014年）

武光华　主编



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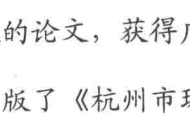
序　言

杭州市环境保护科学研究院（简称杭州市环科院）是杭州市环保局直属的事业单位。近年来，杭州市环科院以“创一流、树权威、促发展”为目标，以“科研立院、人才兴院、管理强院”为方针，求真务实，开拓创新，环境科研工作取得明显成效。2011 年 11 月成立全国环保系统第一家院士工作站，2012 年 3 月获得“十一五”国家环境保护科技工作先进集体称号。

2010 年 6 月杭州市环科院首次编辑出版了《杭州市环境保护科学研究院学术论文集》，收录了 1998—2009 年期间在国内外各类学术期刊上公开发表的论文，获得广泛好评。为进一步总结交流科技成果，杭州市环科院继续组织编辑出版了《杭州市环境保护科学研究院学术论文集（2010—2014 年）》。

目前，杭州正在建设美丽中国先行区和“两美”浙江示范区。希望杭州市环科院在杭州市环保局的正确领导下继续围绕中心，服务大局，致力科研，奋发进取，为综合决策和环境监管提供更加有力的科技支撑，为生态文明建设和环境保护事业作出更大的贡献。

杭州市环境保护局局长 

2015 年 5 月

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第一部分

水环境研究

Thermal Structure and Response to Long-term Climatic Changes in Lake Qiandaohu，a Deep Subtropical Reservoir in China

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Abstract Using the vertical temperature profiles of Lake Qiandaohu from January 2010 to April 2013，we evaluated the monthly and seasonal variations of water temperature and thermocline parameters，and developed empirical models among thermocline depth（TD），thickness（TT），and strength（TS）. We also developed empirical models between TD, TT, TS, and surface-water temperature（0–2 m）（$T_{0\text{-}2\,m}$）, and transparency（Secchi disk depth, SDD）. Additionally, we assessed the changes in TD，TT，and TS over the past 62 yr，based on our empirical models，air temperature data from 1951 to 2012，and SDD data from 1987 to 2012. Lake Qiandaohu is warm monomictic，with a long period of thermal stratification from April until January，and only a short period of mixing in the winter or spring（February or March）. There were significant correlations between SDD and TD（positive）and between SDD and TT（negative）. There was a significant negative correlation between $T_{0\text{-}2\,m}$ and TD during the stratification weakness period（July–February），and a significant positive correlation between $T_{0\text{-}2\,m}$ and TT for all data，including the stratification formation and weakness periods. Air temperature near the lake rose 1.2℃ between 1951 and 2012，corresponding to a 0.8℃ increase in $T_{0\text{-}2\,m}$, and a 0.78 m decrease in SDD between 1987 and 2012. The increase in air temperature and the decrease in SDD caused a decrease in TD and an increase in TT，facilitating the thermal stratification and stability of the lake；therefore，climate warming has had a significant effect on the thermal regime of Lake Qiandaohu.

Thermal structure and stratification in lake ecosystems are physical features that exert important controls on inlake vertical fluxes of dissolved and particulate material（Aeschbach-Hertig et al.，2007），and on lake ecosystem structure and function（O'Reilly et al.，2003；Kaiblinger et al.，2007；Cantin et al.，2011）. Stratification is facilitated by the thermal expansion properties of water，which create a stable vertical density gradient，resulting from heating（or cooling if below 3.98℃）of surface waters. These density gradients are often observed as a region of sharp changes in water temperature（metalimnion）that delineate an upper well-mixed region（epilimnion）from a relatively quiescent deep zone（hypolimnion）. This vertical partitioning of the water column has important implications for the availability of dissolved oxygen，nutrients，light，and microbial substrates（Becker et al.，2009；Wang et al.，2012），as well as the seasonal dynamics，vertical distribution，and migration of phytoplankton and zooplankton（Chen et al.，2009；Becker et al.，2010；Cantin et al.，2011），and the feeding behavior of higher-trophic-level organisms such as zooplankton and fish（Cantin et al.，2011）. Density stratification suppresses vertical transfer between surface and bottom waters and often results in a nutrient-poor，light-rich epilimnion that contrasts with a nutrient-rich，light limited hypolimnion（Macintyre et al.，1999）.

Previous studies have shown that regional-scale air temperatures and surface-water temperatures are highly correlated（Coats et al.，2006；Hampton et al.，2008；Adrian et al.，2009）. Thus，the air temperature increase caused by global climate change is anticipated to have a profound effect worldwide on aquatic ecosystems，including their chemical and physical properties and biotic and ecosystem-scale responses. Over the past 150 yr，human activities such as the burning of fossil fuels and various land-use practices have increased the concentrations of greenhouse gases such as carbon dioxide，methane，ozone，nitrous oxide，and chlorofluorocarbons. The increase in global surface temperature from 1906 to 2005 ranged from 0.56℃ to 0.92℃ and averaged 0.74℃（IPCC 2007）. The linear warming trend over the last 50 yr（0.13℃ per decade）is nearly twice that for the last 100 yr（IPCC 2007）.

Changes to the thermal regime of lakes have already been observed in lakes around the world and include the earlier onset of stratification，longer duration of the stratification period，and a decrease in thermocline depth with an increase in thermocline thickness（Winder and Schindler 2004；Coats et al.，2006；Stainsby et al.，2011）. However，certain climate change scenarios predict deeper thermoclines in northern lakes because of the decline in concentration of colored dissolved organic carbon（CDOC）resulting from temperature increases and longer periods of drought，which are expected to decrease the amount of catchment organic matter brought to lakes by precipitation runoff（Fee et al.，1996）. In addition，increasing temperatures are associated with a deepening thermocline in small lakes（0.5 km^2）and a shallowing thermocline in larger lakes（73.6 km^2）；these contrasting responses may be the result of differences in lake size and the diminishing influence of water clarity on mixing depth（King et al.，1999）. Whether climate change will lead to deeper or shallower thermoclines remains uncertain；however，a change in thermocline depth is expected，and additional field and simulation studies are required to better understand and predict the change（s）.

Changes in thermal structure might be responsible for circulation patterns that influence the vertical distribution of chemical factors such as nutrient and oxygen concentrations（Wilhelm and Adrian 2008）. In addition，climate-stimulated biological responses in lakes are an important issue，and several studies and reviews have shown coupling between lake-water temperatures and individual organism physiology，population abundance，and community structure（Winder and Hunter 2008；Cantin et al.，2011；Paerl and Paul 2012）. For example，in Lake Tahoe during the 1 980 s, the phytoplankton community structure was associated most strongly with resource availability, whereas after the late 1 990 s, the phytoplankton community structure was mostly associated with intensified stratification (Winder and Hunter2008).

Although the profound effects of water temperature, thermal structure, and stratification on the physical, chemical, and biological characteristics of many deep lakes are well known, few studies have quantified such effects in reservoirs (Becker et al., 2009; Jones et al., 2011; Wang et al., 2012). Many reservoirs in China supply the water for industry, agriculture, and residential drinking water. In addition, the water quality in many of these reservoirs has declined over the last 20 yr, mostly because of the increasing trophic status (Wang et al., 2004). Thus, an understanding of the thermal regime, the factors affecting it, and its response to changing climate is critical for developing strategies to adaptively manage water quality in reservoirs.

Lake Qiandaohu (formerly Xin'anjiang Reservoir) is a large, artificial, deep-water lake, and a nationally protected drinking water source. Water-quality problems have been documented, and short-term algal blooms have appeared in the lake since the 1 990 s and have primarily been attributed to increases in nitrogen and phosphorus loading following the conversion of land in the watershed to agricultural and urban uses (Zhai et al., 2014). While nitrogen and phosphorus loading remains a key management concern under the current protection efforts, it is recognized that the lake is subject to other interrelated stressors, including other pollutants and climate change. Given the effects of climate change observed in other lakes, there is a need to investigate whether similar changes are occurring in Lake Qiandaohu. Therefore, using Lake Qiandaohu as an example, the aims of this study are to (1) analyze the thermocline characteristics, including depth, thickness, and strength; (2) assess the factors affecting the thermocline; and (3) qualitatively describe the response of the thermal structure to long-term climatic changes.

1 Methods

Study lake and sampling sites—Lake Qiandaohu (29°22′–29°50′N, 118°369–119°14′E) was originally called Xin'anjiang Reservoir when it was built in 1959 and is located in the west of Zhejiang Province and the south of Anhui Province, approximately 70 km from Hangzhou City (Fig. 1, circle). The lake is a long and narrow reservoir that has many bays, and the greatest length and width of its bays are 150 km and 50 km, respectively. In the lake, there are numerous islands (the name "Qiandao" means that there are a thousand islands). Lake Qiandaohu has a water area of 580 km^2, a mean 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 water level is 108 m. The lake is a popular destination for sports and recreation year-round.

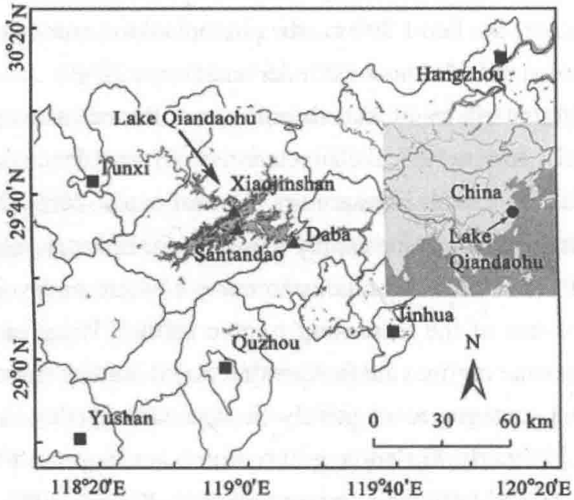

Fig.1 Location of Lake Qiandaohu(circle), the distribution of meteorological stations(squares), and sammling sites(triangles)

Forty field investigation cruises (one per month) were conducted between January 2010 and April 2013. Monthly data were considered on a seasonal basis, with the seasons defined as follows: winter, December–February; spring, March–May; summer, June–August; and autumn, September–November.

At the beginning of each month, the water temperature depth profile was measured at three sites (Daba, Santandao, and Xiaojinshan; Fig. 1, triangle). Sampling sites were positioned using the global positioning system (GPS) with an accuracy of 2.0 m.

Measurement of water temperature—Using a 9 channel multiparameter water-column profiler (xrx-620, Richard Brancker Research Limited), the vertical depth (±0.05%) and temperature (±0.002℃) profiles were recorded. We only used data from 0.2 m to the maximum depth; data collected during the ascent of the profiler were discarded.

The xrx-620 profiler was lowered to the bottom of the lake and slowly pulled back towards the surface using an automatically controlled winch. The sampling rate of the xrx-620 profiler is 2 s, and the pulling speed was kept at approximately 10 cm s^{-1}. Thus, the data were recorded every 0.2 m and stored in the memory of the xrx-620 profiler.

A Kestrel 4 500 weather tracker (Nielsen-Kellerman) was configured to synchronously record four parameters at each site: wind speed, wind direction, air temperature, and relative humidity. A standard 30-cm-diameter Secchi disk was used to measure transparency (Kalff 2002). In addition, data on yearly mean transparency in Lake Qiandaohu from 1987 to 2012 were calculated from the monthly monitoring data from the Chun'an Environmental Monitoring Station.

To determine the response of thermal structure and stratification to long-term climate change in Lake Qiandaohu, we downloaded data on the daily average air temperature from 1951 to 2012 from the China meteorological data-sharing service system (http: //cdc.cma.gov.cn/home.do). We obtained data from the five closest meteorological stations: Hangzhou (30°149′N, 120°10′E), Tunxi (29°43′N, 118°17′E), Yushan (28°41′N, 118°15′E), Quzhou (29°00′N, 118°54′E), and Jinhua (29°07′N, 119°39′E), which were 70, 50, 80, 45, and 55 km from the lake, respectively (Fig. 1, square). From the daily average air temperature data, we calculated the monthly and yearly mean values for each of the five meteorological stations. These data showed that the off-site temperature data were characteristic of the region.

Thermocline detection—The widely used gradient criterion (GC) method for determining the thermocline requires that the vertical gradient of temperature be larger than a certain fixed value. However, there is no objective way to determine the criterion, which ranges from 0.05℃ m^{-1} to 2℃m^{-1} (Coloso et al., 2011; Hao et al., 2012). For example, the criterion value of 0.05℃m^{-1} is used for the Chinese shelf (>200 m; Zou et al., 2001), 0.2℃m^{-1} is used for the Chinese shelf (≤200 m; Hao et al., 2012), and 1℃m^{-1} is used in Canadian Shield lakes (Fee et al., 1996).

The choice of this criterion is arbitrary and varies with different regions. In the present study, we used the uniform criterion of 0.2℃ m^{-1} based on the water temperature profile measured in Lake Qiandaohu, which is widely used in other lake waters (Wilhelm and Adrian 2008). We chose this criterion value based on experience with the temperature profiles in Lake Qiandaohu. Other criterion values are possible, but we did not compare alternatives in this study.

To study the distribution and variability of thermocline depth (TD), thickness (TT), bottom (TB), and strength (TS), the upper and lower thermocline boundaries had to be determined accurately. TD and TB are defined as the upper and lower boundary depths, respectively, of the thermocline layer. Thermocline depth is the depth of the upper thermocline boundary, and thermocline thickness is the difference between the upper and lower thermocline boundaries. ΔD and ΔT are defined as the depth and temperature differences between TD and TB, respectively. Strength is simply defined as ΔT: ΔD and does not consider the fine structures within the thermocline layer.

Data analysis and testing the models—Statistical analyses, including mean values, linear and nonlinear fitting, and regression and correlation analyses, were performed using Statistical Program for Social Sciences (SPSS) 17.0 software. Significance levels are reported as significant if $p < 0.05$.

2 Results

Monthly and seasonal variations of water temperature—The annual changes in water temperature from January 2010 to April 2013 for three different layers at the three sites in Lake Qiandaohu are shown in Fig. 2 a–c. For surface water, the three sites showed similar dome-shaped seasonal patterns of temperature with a peak in late summer (August). Surface-water temperatures ranged from <10℃ in February or March to >32℃ in August. The seasonal variations of water temperature were summer .spring and autumn. winter, with a maximum in July or August and a minimum in February or March. From February to August, the water temperature gradually increased to the maximal value and then gradually decreased from August to February of the next year. The middle-layer water temperature ranged from <10℃ in April to >21℃ in November. In the middle layer, the month with the highest water temperature markedly lagged 3 months behind that of the surface layer. In contrast, the month of the lowest middle-layer water temperature was consistent with that of the surface layer. For the bottom layer, there were no monthly and seasonal variations in water temperature, confirming that the water temperature of the bottom water layer was not affected by seasonal variations of air temperature.

Generally, Lake Qiandaohu was isothermal in winter and stratified in spring, summer, and fall (Fig. 2 a–c). At the beginning of the stratification period (March–April), the difference in water temperature between the surface and the bottom of the lake was less than 5℃. However, during the rest of the stratification period, from May to December, the difference in water temperature between the surface and the bottom of the lake was much greater, between 5℃ and 20℃.

Monthly and seasonal variations of thermocline parameters—The monthly and seasonal variations of the mean thermocline depth, thickness, and strength at the three sites in Lake Qiandaohu are presented in Fig. 2 d, e, and f, respectively. The thermocline was generally shallow from March to August and deep from September to January. During the former warm period, the seasonal surface thermocline developed and matured, and the thermocline depth was relatively stable at a low value near 3.0 m. From the beginning of September, the thermocline depth gradually increased and reached the maximal depth near 40 m in January or February of the following year. An isothermal was recorded in February 2010 and in March 2011 and 2012; therefore, there were no thermocline depth values for these months (Fig. 2 d).

There was a marked monthly variation in thermocline thickness (Fig. 2 e). From the beginning of February or March, the thermocline thickness gradually increased and reached a maximum of 25–30 m in July or August and then gradually decreased to 0 m in February or March of the following year (Fig. 2 e). When the seasonal surface thermocline matured in July or August, the maximal thermocline thickness was recorded. During the period of stratification weakness of the thermocline (July–February), there was a significant negative linear relationship between thermocline depth and thermocline thickness (Fig. 3 a; Table 1). However, during the period of stratification formation of the thermocline (March–June), there was no significant correlation between thermocline depth and thermocline thickness.

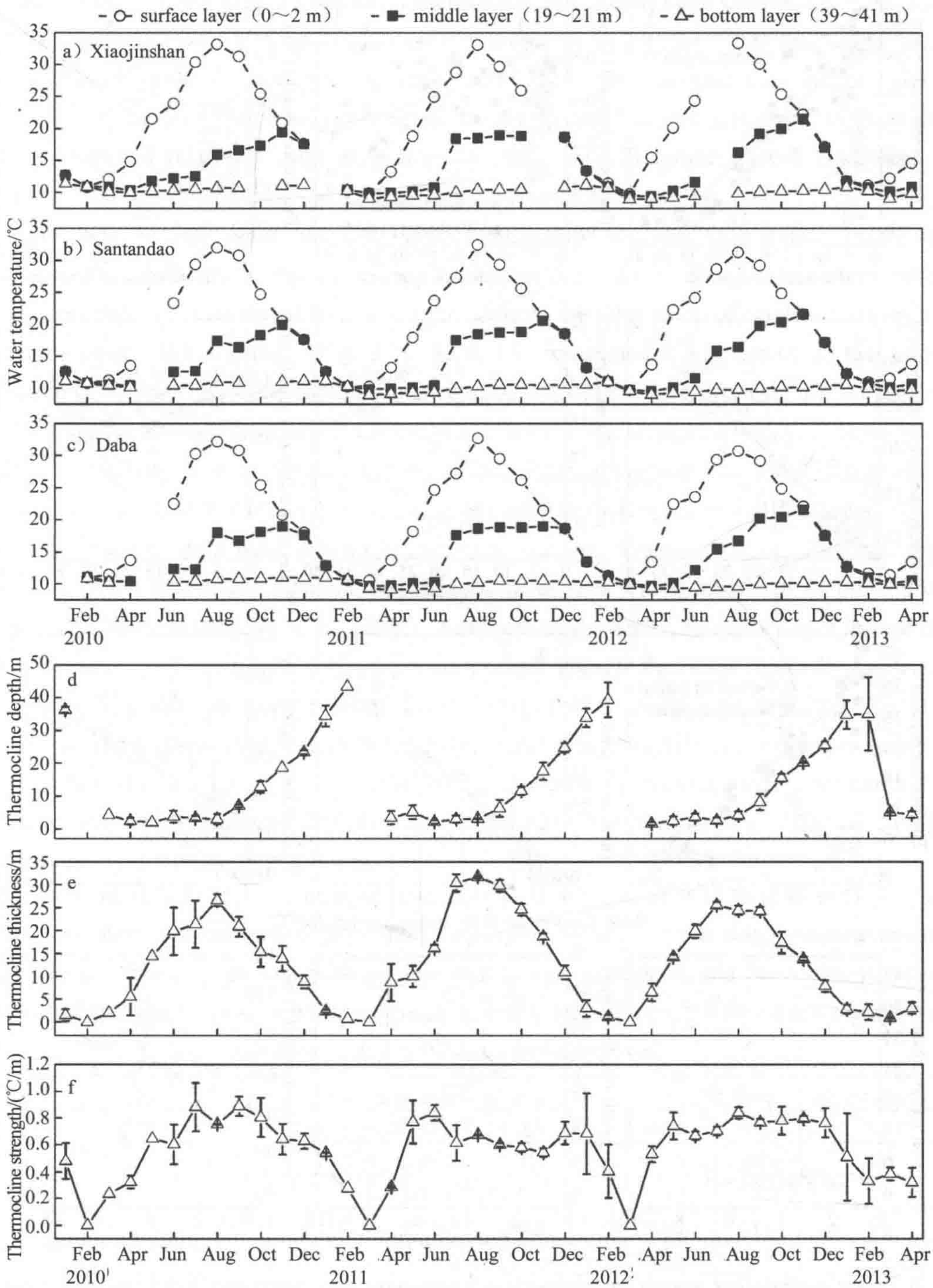

Fig. 2. Monthly variations of water temperature of the surface (0–2.0 m), middle (19–21 m), and bottom (39–41 m) layers at (a) Xiaojinshan, (b) Santandao, and (c) Daba; and (d) thermocline depth, (e) thermocline thickness, and (f) thermocline strength from January 2010 to April 2013 in Lake Qiandaohu