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Thermal structure and response to long-term climatic changes in Lake Qiandaohu, a deep subtropical reservoir in China

Yunlin Zhang,[1,a,*] Zhixu Wu,[2] Mingliang Liu,[3] Jianbo He,[3] Kun Shi,[1] Mingzhu Wang,[1] and Zuoming Yu[3]

[1] 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, China
[2] Chun'an Environmental Monitoring Station, Hangzhou, China
[3] Institute of Environmental Protection Science, Hangzhou, China

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) ($T_{0\text{–}2\text{ m}}$), 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 $T_{0\text{–}2\text{ m}}$ and TD during the stratification weakness period (July–February), and a significant positive correlation between $T_{0\text{–}2\text{ m}}$ and TT for all data, including the stratification formation and weakness periods. Air temperature near the lake rose 1.2°C between 1951 and 2012, corresponding to a 0.8°C increase in $T_{0\text{–}2\text{ m}}$, 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 in-lake 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°C) 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°C to 0.92°C and averaged 0.74°C (IPCC 2007). The linear warming trend over the last 50 yr (0.13°C 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

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[*] Corresponding author: yunlinzhang@yeah.net

[a] Present address: Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China

lakes (0.5 km²) and a shallowing thermocline in larger lakes (73.6 km²); 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 1980s, the phytoplankton community structure was associated most strongly with resource availability, whereas after the late 1990s, the phytoplankton community structure was mostly associated with intensified stratification (Winder and Hunter 2008).

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 1990s 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.

Methods

Study lake and sampling sites—Lake Qiandaohu (29°22′–29°50′N, 118°36′–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 km², a mean depth of 30 m, a water volume of 178.4×10^8 m³, and a basin area of 10,480 km² when the normal water storage water level is 108 m. The lake is a popular destination for sports and recreation year-round.

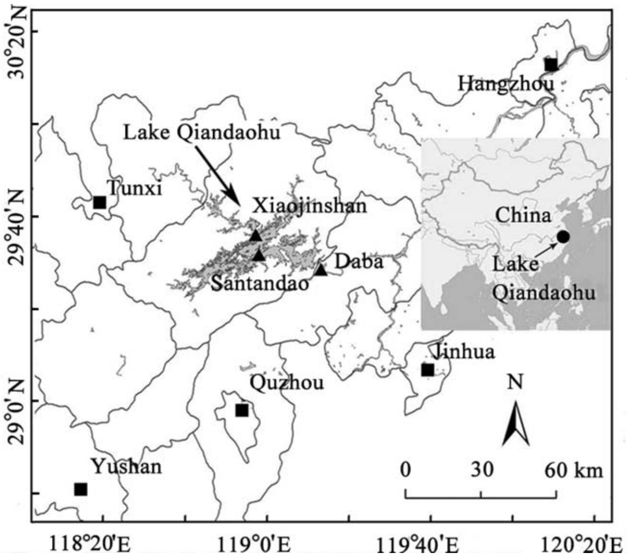

Fig. 1. Location of Lake Qiandaohu (circle), the distribution of meteorological stations (squares), and sampling sites (triangles).

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°C) 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 4500 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°14′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°C m^{-1} to 2°C m^{-1} (Coloso et al. 2011; Hao et al. 2012). For example, the criterion value of 0.05°C m^{-1} is used for the Chinese shelf ($>$ 200 m; Zou et al. 2001), 0.2°C m^{-1} is used for the Chinese shelf ($\leq$ 200 m; Hao et al. 2012), and 1°C 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°C 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 $\Delta T : \Delta D$ 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 $p < 0.05$.

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. 2a–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°C in February or March to $>$ 32°C 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°C in April to $>$ 21°C 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. 2a–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°C. 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°C and 20°C.

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. 2d, 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. 2d).

There was a marked monthly variation in thermocline thickness (Fig. 2e). 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

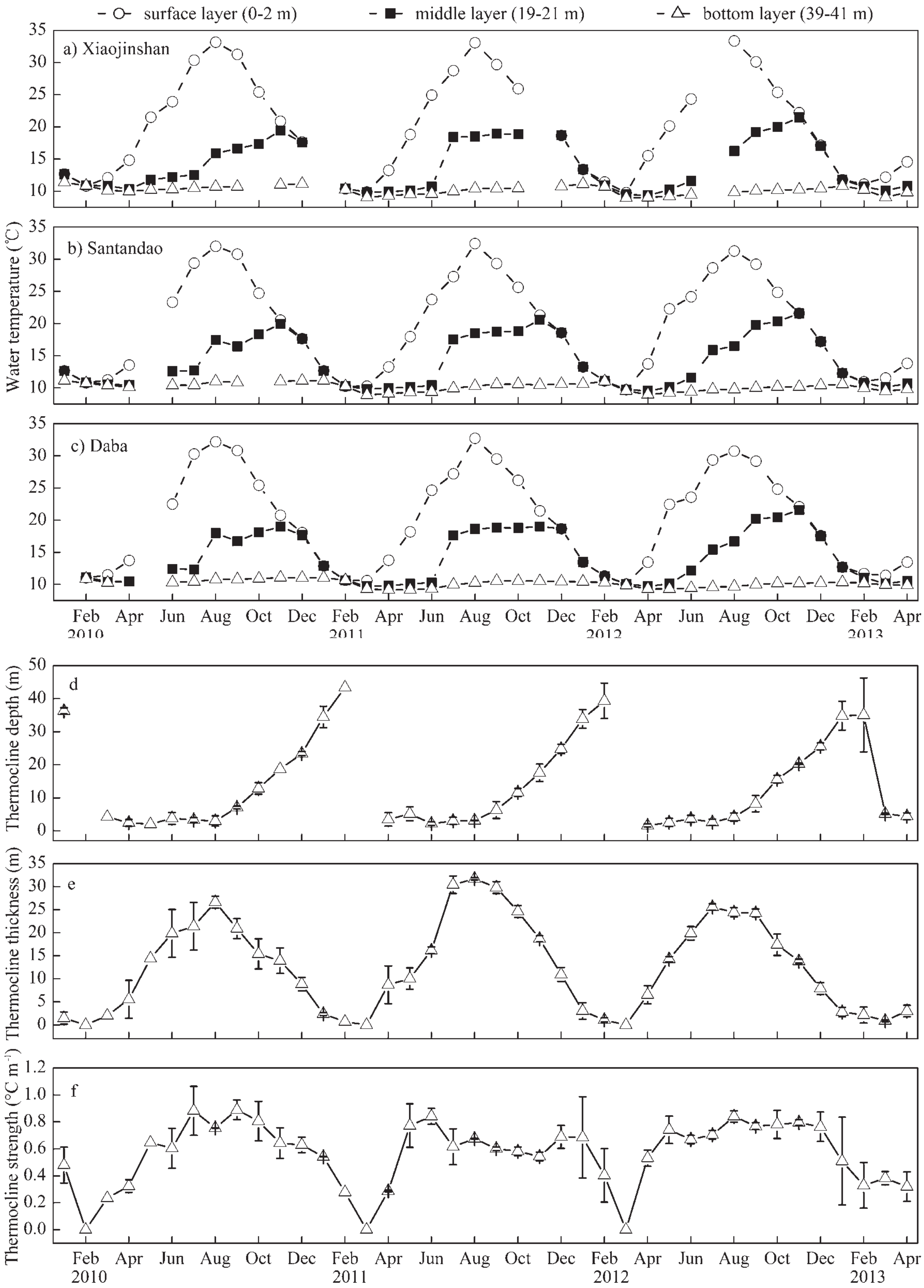

Fig. 2. Monthly variations of water temperature of the surface (0–2.0 m), middle (19–21 m), and bottom (39–41 m) layers at (a) Xiaojinshan, (b) Santandao, and (c) Daba; and (d) thermocline depth, (e) thermocline thickness, and (f) thermocline strength from January 2010 to April 2013 in Lake Qiandaohu.

following year (Fig. 2e). 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. 3a; 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.

The monthly and seasonal variations of thermocline strength in Lake Qiandaohu (Fig. 2f) were largely consistent with those of thermocline thickness. In the late winter and early spring (February and March), there was no thermocline (vertical temperature gradient $< 0.2°\text{C m}^{-1}$). From February or March to July or August, the thermocline strength gradually increased and then remained relatively high at nearly $0.8°\text{C m}^{-1}$ until December. From December to February or March, the thermocline strength rapidly decreased to 0 (Fig. 2f).

There was a significant negative linear relationship between thermocline depth and thermocline strength during the period of stratification weakness (July–February), but there was no significant correlation between these parameters during the formation of stratification of the thermocline layer (March–June) (Fig. 3b; Table 1). This pattern was similar to that of the relationship between thermocline depth and thermocline thickness. There was a significant positive linear relationship between thermocline thickness and thermocline strength (Fig. 3c; Table 1).

Factors affecting water temperature and thermal structure—There was a highly significant positive correlation between air temperature and surface-water temperature ($r^2 = 0.80$, $p < 0.001$; Fig. 3d; Table 1), indicating that air temperature was the dominant factor affecting water temperature. Such significant positive correlations have been widely observed in other lakes (Coats et al. 2006; Hampton et al. 2008; Adrian et al. 2009). As water depth increased, the determination coefficient between air temperature and water temperature markedly decreased. However, in the middle water layer, there was still a significant correlation ($r^2 = 0.20$, $p < 0.001$; Fig. 3e; Table 1), and in the bottom water layer, there was no significant correlation between air temperature and water temperature (Fig. 3f). The water temperature of the bottom water layer was not rapidly affected by the air temperature but was slowly affected by the surface-water layer through heat transfer.

While the temperature of the epilimnetic water exhibited a rapid and direct response to climatic conditions, the deep hypolimnetic water was shielded from the major sources of energy. In contrast, temperatures in the hypolimnetic water exhibited a much more complex behavior and may undergo warming or cooling trends depending on the lake morphometry (Gerten and Adrian 2001) and season (Straile et al. 2003). Therefore, epilimnetic water temperature is considered to be a good indicator of climate change in lakes because it reflects climatic forcing more immediately and more sensitively than any other lake parameter (Livingstone and Dokulil 2001; Adrian et al. 2009).

The factors affecting thermal structure include heat flux (water temperature), light penetration (transparency or diffuse attenuation coefficient), and lake morphometry (size, length, and fetch). For the seasonal and spatial variations of thermal structure in a specific lake, heat flux and light penetration are usually the most important driving factors. Therefore, water temperature and transparency were considered the major factors affecting the thermal structure in Lake Qiandaohu.

During the period of stratification weakness (July to February), there was a highly significant negative linear relationship between water temperature at the surface layer (0–2 m) and thermocline depth (Fig. 3g; Table 1). In contrast, there was no significant correlation between these two parameters during the formation of stratification (March to June). If the data of thermocline depth during the stratification formation period (March–June) were included, the determination coefficient markedly decreased (from 0.94 to 0.31), indicating that water temperature at the surface layer (0–2 m) did have a significant effect on the thermocline depth during the stratification weakness (July to February) despite the water temperature having no effect on thermocline depth during the stratification formation (March–June).

There were significant positive linear relationships between water temperature at the surface layer (0–2 m) and thermocline thickness ($r^2 = 0.91$; Fig. 3h; Table 1) and between water temperature at the surface layer and thermocline strength ($r^2 = 0.52$; Fig. 3i; Table 1) for all data, including the stratification formation and weakness periods.

Light penetration is responsible for the formation of heating gradients, which affect water density and the establishment of the thermocline, and an increase in light penetration will cause deeper water to be heated. Therefore, transparency had a positive effect on thermocline depth and a negative effect on thermocline thickness. There was a significant positive correlation between transparency and thermocline depth (Fig. 3j; Table 1), and a negative correlation between transparency and thermocline thickness (Fig. 3k; Table 1). There was no significant correlation between transparency and thermocline strength (Fig. 3l), suggesting that thermocline strength was not a good indicator of the thermal structure of Lake Qiandaohu.

The transparency of the water in Lake Qiandaohu has decreased by 0.78 m in the last 26 yr (1987–2012), which is statistically significant; the mean rate of decrease has been 0.3 m per decade (Fig. 4). Such a decrease in transparency would cause a 2.72 m decrease in the thermocline depth and a 1.62 m increase in the thermocline thickness, based on the correlations in Fig. 3j,k, which would affect the lake thermal stratification and stability. There is uncertainty regarding the variation of thermocline depth and thickness because of the relatively low determination coefficients between transparency and thermocline depth and transparency and thermocline thickness (Fig. 3j,k; Table 1).

After considering the seasonal variations in the three thermocline parameters (Fig. 2d–f), the correlations between water temperature at the surface layer and thermocline parameters (Fig. 3g–i; Table 1), and the correlations between transparency and thermocline parameters (Fig. 3j,k;

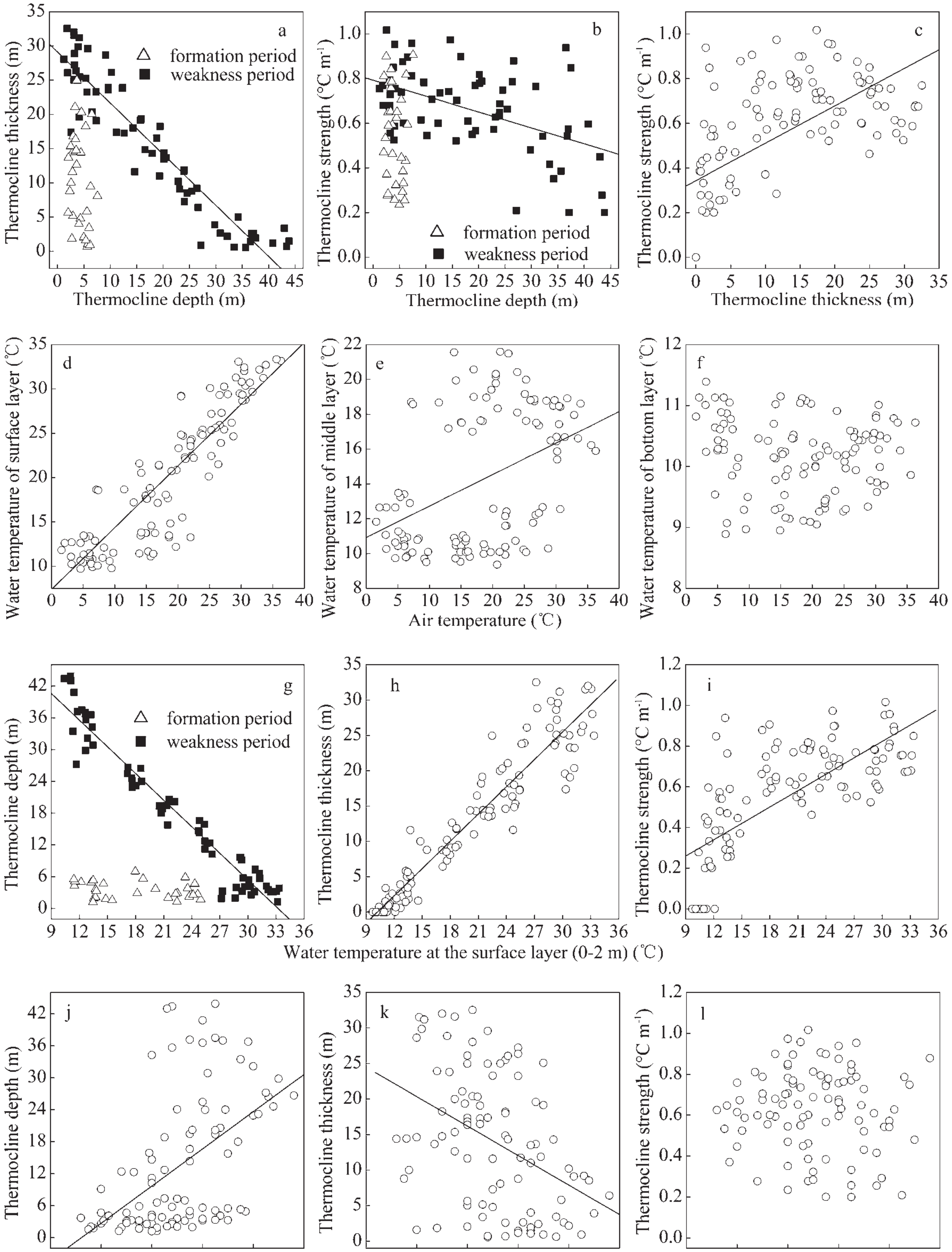

Fig. 3. Linear relationships among the thermocline parameters: (a) depth and thickness, (b) depth and strength, and (c) thickness and strength; between air temperature and water temperature of the (d) surface (0–2 m), (e) middle (19–21 m), and (f) bottom (39–41 m) layers; between water temperature at the surface layer (0–2 m) and (g) thermocline depth, (h) thermocline thickness, and (i) thermocline strength; and between transparency and (j) thermocline depth, (k) thermocline thickness, and (l) thermocline strength in Lake Qiandaohu. Data during the stratification formation and weakness periods are shown, respectively, in Fig. 3a, b, g.

Table 1. Correlation analyses among thermocline parameters, air temperature, water temperature, and transparency ($p < 0.01$). For the relationships between the thermocline depth and thermocline thickness, thermocline strength, and 0–2 m water temperature, only the data during the period of stratification weakness (July to February) were included.

	Linear fitting*	r^2	n	Figure number
Thermocline parameters	$\mathrm{TT} = -0.747\mathrm{TD} + 29.121$	0.89	68	3a
	$\mathrm{TS} = -0.007\mathrm{TD} + 0.793$	0.25	68	3b
	$\mathrm{TS} = 0.017\mathrm{TT} + 0.343$	0.37	113	3c
Air and water temperature	$T_{0\text{–}2\ \mathrm{m}} = 0.729T_{\mathrm{Air}} + 6.652$	0.80	113	3d
	$T_{19\text{–}21\ \mathrm{m}} = 0.190T_{\mathrm{Air}} + 10.709$	0.20	113	3e
Water temperature and thermocline parameters	$\mathrm{TD} = -1.68T_{0\text{–}2\ \mathrm{m}} + 55.66$	0.94	68	3g
	$\mathrm{TT} = 1.29T_{0\text{–}2\ \mathrm{m}} - 13.19$	0.91	113	3h
	$\mathrm{TS} = 0.027T_{0\text{–}2\ \mathrm{m}} + 0.017$	0.52	113	3i
Transparency and thermocline parameters	$\mathrm{TD} = 3.49\mathrm{SDD} - 4.29$	0.27	99	3j
	$\mathrm{TT} = -2.08\mathrm{SDD} + 24.49$	0.17	99	3k

* TT, thermocline thickness; TD, thermocline depth; TS, thermocline strength; $T_{0\text{–}2\ \mathrm{m}}$, 0–2 m water temperature; T_{Air}, air temperature; $T_{19\text{–}21\ \mathrm{m}}$, 19–21 m water temperature; SDD, transparency.

Table 1), we concluded that thermocline depth and thickness were better indicators of the thermal structure of Lake Qiandaohu than thermocline strength.

Response of thermal stratification to climate change—Yearly mean air temperatures for the last 62 yr (1951–2012) for each of the five meteorological stations surrounding Lake Qiandaohu and for all five stations together are shown in Fig. 5. Over these 62 yr, a significant increase ($p < 0.001$) in yearly mean air temperature has occurred at each of the five stations. The increased rate, shown by the slope of the line, varies considerably between the five stations, with the greatest increase in air temperature at 0.30°C per decade, which was based on the linear fitting recorded near the city of Hangzhou (Fig. 5a; Table 2) and partly attributed to the urban heat island effect. The smallest increase in air temperature of 0.11°C per decade was observed in Quzhou (Fig. 5d; Table 2). When all five sites are considered together, the mean increase in air temperature is 0.19°C per decade (Fig. 5f; Table 2), which is close to the global warming trend of 0.13°C per decade over the last 50 yr (IPCC 2007).

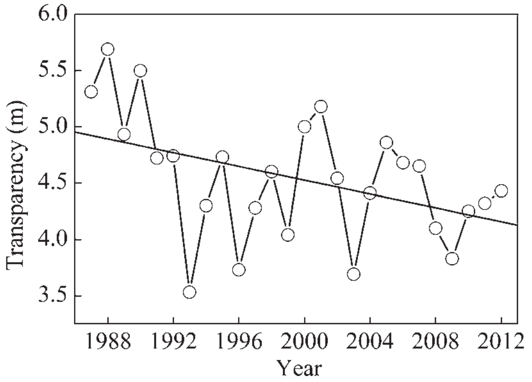

Fig. 4. Variation in yearly mean transparency (SDD) in Lake Qiandaohu from 1987 to 2012. The line represents the linear fitting of transparency (SDD) vs. year (yr). The linear fitting relationship was as follows: $\mathrm{SDD} = -0.030\ \mathrm{yr} + 65.69$ ($n = 26$, $r^2 = 0.18$, $p = 0.026 < 0.05$).

We then qualitatively assessed the effect of the increase in air temperature on the thermal structure of the lake. In the past 62 yr, the yearly mean air temperature surrounding Lake Qiandaohu has increased by 1.2°C, which is based on the mean increase in slope of 0.19°C per decade (Fig. 5f; Table 2). Based on the linear relationship between air temperature and water temperature (Fig. 3d; Table 1), the increase of 1.2°C in air temperature would cause a 0.8°C increase in surface-water temperature. This increase in surface-water temperature would in turn cause a 1.4 m decrease in the thermocline depth during the period of stratification weakness (July–February), a 1.1 m increase in thermocline thickness, and a 0.22°C m^{-1} increase in thermocline strength according to the correlations in Fig. 3g–i and Table 1.

Discussion

Thermal stratification and mixing are important physical phenomena in deep lakes and reservoirs. In the present 3 yr study, we documented the seasonal variations of thermocline depth, thickness, and strength in Lake Qiandaohu, a deep reservoir in China (Fig. 2d–e). Lake Qiandaohu was stratified for most of the year, with only a short mixing period in winter, which is consistent with many similar subtropical or tropical reservoirs (Chen et al. 2009; Wang et al. 2012). Therefore, Lake Qiandaohu is a warm monomictic water body. Stratification could be transient or persistent, vary at timescales of hours (Rueda and Schladow 2009) to decades (Verburg et al. 2003), and decay to near-vertical homogeneity as mixing mechanisms such as wind and convection outweigh the stabilizing inputs of surface heating.

At a macroscopic scale, thermocline depth is largely determined by parameters of lake size such as the length or fetch (Kling 1988; Kalff 2002; Von Einem and Granéli 2010) and is modulated by differences in heat flux (Churchill and Kerfoot 2007) and factors affecting light penetration (Fee et al. 1996), such as the concentration of CDOC, especially in smaller lakes (< 5 km^2; Pérez-Fuentetaja et al. 1999; Von Einem and Granéli 2010). The effect of lake size on thermocline depth reflects the differential effect of wind-induced mixing in small vs. large

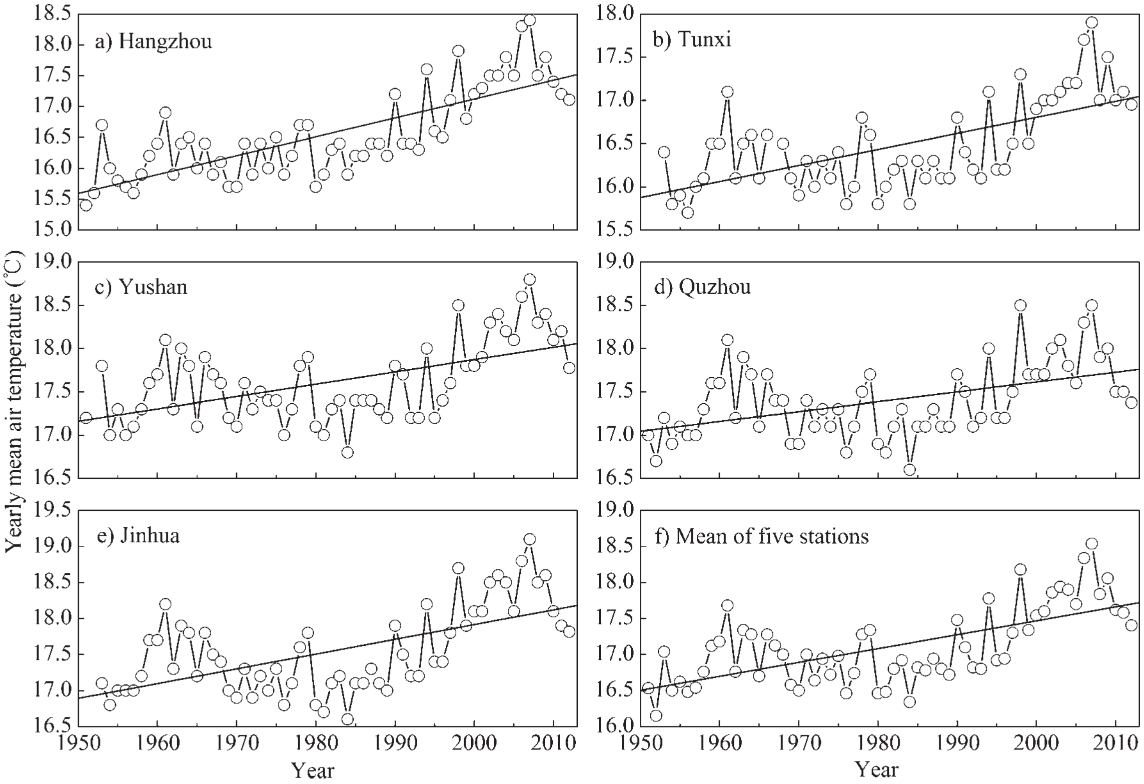

Fig. 5. Variations of yearly mean air temperature from 1950 to 2012 for five meteorological stations surrounding Lake Qiandaohu: (a) Hangzhou, (b) Tunxi, (c) Yushan, (d) Quzhou, (e) Jinhua, and (f) the mean of the five stations. The straight line represents the linear fitting of air temperature (T_{Air}) vs. year (yr).

lakes, so any changes in wind regimes are likely to affect the thermal structure of a lake. Therefore, many empirical and semi-empirical models have been developed for predicting thermocline depth using lake surface area and wind fetch (Kling 1988; Kalff 2002). The mean thermocline depth for our three study sites in Lake Qiandaohu during 2010 to 2013 was 13.03 m, which was very close to the calculated value of 14.87 m from the model employed for worldwide lakes that used a lake surface area of 580 km^2 (Kalff 2002).

Over a large spectrum of lake sizes in the Canadian Shield, surface area was the most important determinant of thermocline depth in lakes > 5 km^2; however, in small lakes (area < 5 km^2), water transparency was a more relevant factor than area (Pérez-Fuentetaja et al. 1999). In tropical lakes, Kling (1988) found that transparency explained 71% of the variation in thermocline depth, whereas lake area explained only 2%. A strong positive relationship between thermocline depth and water transparency in Lake Qiandaohu (Fig. 3j) and other tropical and temperate lakes (Kling 1988; Pérez-Fuentetaja et al. 1999) suggests that reductions in buoyant resistance to vertical mixing caused by deeper penetration of solar radiation are important in establishing mixing depths.

Table 2. Linear fitting relationships of yearly mean air temperature vs. year for five meteorological stations surrounding Lake Qiandaohu (Hangzhou, Tunxi, Yushan, Quzhou, Jinhua) and the mean of the five stations ($n = 62$, $p < 0.01$).

Station	Linear fitting		r^2
	Slope	Intercept	
Hangzhou	0.030	−43.98	0.59
Yushan	0.014	−10.52	0.30
Jinhua	0.020	−23.09	0.35
Tunxi	0.018	−20.26	0.40
Quzhou	0.011	−5.07	0.23
Mean of five stations	0.019	−21.09	0.42

At a microscopic scale, the thermal structure of a specific lake is influenced by both natural (meteorological and hydrological) factors and anthropogenic (reservoir operation and management policy) factors. For example, a numerical simulation study in Liuxihe Reservoir in Guangdong Province, China, showed that continuous warming would cause greater water-column stability and increased duration of stratification than the absence of continuous warming, whereas irregular large discharge events might reduce stability and lead to early mixing in autumn (Wang et al. 2012).

A distinct trend in increasing yearly mean air temperature and water temperature resulting from human activities has been observed worldwide (Livingstone 2003; Arhonditsis et al. 2004; Wang et al. 2012), and the increase is expected to continue for the next several decades. In the last 50 yr, the linear warming trend was 0.13°C per decade. For the next two decades, a warming of approximately 0.2°C per decade was projected from a special report on emission scenarios. Even if the concentrations of all greenhouse gases and aerosols could be maintained at the levels observed in the year 2000, a further warming of approximately 0.1°C per decade is expected (IPCC 2007). Therefore, changes in thermal structure resulting from climate change might be responsible for the circulation patterns influencing the vertical distribution of the biota and the nutrient and oxygen concentrations throughout the water column in lakes.

Our qualitative assessment of the effect of global warming on the thermal structure of Lake Qiandaohu showed that (1) thermocline depth during stratification weakness (July–February) decreased by 1.4 m, (2) thermocline thickness increased by 1.1 m, and (3) thermocline strength increased by 0.22°C m^{-1} when the mean air temperature increased from 15.96°C to 17.14°C. Our results confirmed previous field observations and simulation results, which showed that an increase in air temperature is accompanied by a decrease in thermocline depth and an increase in thermocline thickness (Stainsby et al. 2011; Lee et al. 2012; Wang et al. 2012).

The increase in thermal stability resulting from the air temperature increase and the transparency decrease could be caused by water temperatures in the epilimnion and metalimnion increasing faster than those in the hypolimnion. Consequently, the stratification period would be lengthened, and mixing would be reduced, which are expected to have significant adverse effects on the lake ecosystem. Stratification during the summer acts as a barrier, restraining the mixing of the water column. The warm water in the epilimnion is unable to move through the cold, dense water of the hypolimnion. Because of incomplete mixing of the water column and a lack of light for photosynthesis at the hypolimnion, the water column can become anoxic (Elçi 2008; Sahoo and Schladow 2008). Furthermore, turbidity usually peaks in the thermocline region, which is closely related to the location of the maximum density gradient, so low turbulence stabilizes the sediments in the vertical water column (Elçi 2008). As a result, the degradation of water quality in the summer resulting from thermal stratification has been observed in many reservoirs and lakes around the world (Elçi 2008; Merino-Ibarra et al. 2008; Wilhelm and Adrian 2008).

Except for its effects on water quality, the increasing duration of stratification also increases the effect of stratification on the functional phytoplankton composition and community (Wilhelm and Adrian 2008). In Lake Tahoe, the phytoplankton community structure was most strongly associated with resource availability during the 1980s, whereas intensified stratification was the dominant factor explaining community structure after the late 1990s (Wilhelm and Adrian 2008). A long-term scale study from the meta-analysis of over 200 paleolimnological records from Northern Hemisphere lakes showed a strong correlation between long-term increases in air temperature and ice-out records and compositional changes in diatom communities (Rühland et al. 2008). In addition, the decrease in mixing depth, resulting from increased stratification, is the causal factor for the spring algal bloom in certain reservoirs (Berger et al. 2006; Chen et al. 2009). Therefore, further studies should be carried out to investigate the effects of the thermal structure of Lake Qiandaohu on water-quality parameters, including dissolved oxygen, nutrients, and suspended solid concentrations, and the phytoplankton and zooplankton communities.

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