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Simulation and Exploration of the Mechanisms Underlying the Spatiotemporal Distribution of Surface Mixed Layer Depth in a Large Shallow Lake

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ABSTRACT

The aquatic eco-environment is significantly affected by temporal and spatial variation of the mixed layer depth (MLD) in large shallow lakes. In the present study, we simulated the three-dimensional water temperature of Taihu Lake with an unstructured grid with a finite-volume coastal ocean model (FVCOM) using wind speed, wind direction, short-wave radiation and other meteorological data measured during 13–18 August 2008. The simulated results were consistent with the measurements. The temporal and spatial distribution of the MLD and the possible relevant mechanisms were analyzed on the basis of the water temperature profile data of Taihu Lake. The results indicated that diurnal stratification might be established through the combined effect of the hydrodynamic conditions induced by wind and the heat exchange between air and water. Compared with the net heat flux, the changes of the MLD were delayed approximately two hours. Furthermore, there were significant spatial differences of the MLD in Taihu Lake due to the combined impact of thermal and hydrodynamic forces. Briefly, diurnal stratification formed relatively easily in Gonghu Bay, Zhushan Bay, Xukou Bay and East Taihu Bay, and the surface mixed layer was thin. The center of the lake region had the deepest surface mixed layer due to the strong mixing process. In addition, Meiliang Bay showed a medium depth of the surface mixed layer. Our analysis indicated that the spatial difference in the hydrodynamic action was probably the major cause for the spatial variation of the MLD in Taihu Lake.

Key words: mixed layer depth, temporal and spatial distribution, Taihu Lake, thermal stratification

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1. Introduction

The abundance, composition and vertical distribution of phytoplankton in the euphotic zone can be affected by various physical, chemical, and biological processes (Doyon et al., 2000). Phytoplankton agglomerate in shallow water due to the vertical attenuation of photosynthetically active radiation (PAR) and the demand of algal photosynthesis. Hence, the dynamic action of the surface mixed layer (ML), which is defined as a quasi-homogeneous region where there is little variation in temperature or density with depth (Kara et al., 2000), is particularly important for phytoplankton, even the whole aquatic ecosystem. The establishment and destruction of stratification, as well as changes in its depth, can affect the consumption and

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supply of nutrients (Anis and Singhal, 2006) and, subsequently, algal growth. Turbulence in the ML can also control the movement and distribution of phytoplankton, which in turn affects their photosynthesis rate, as well as the frequency, duration, and intensity of algal blooms (Obata et al., 2009). Therefore, the mixed layer depth (MLD) is critical to species succession, distribution, and the primary productivity of phytoplankton in the water column (Raybov et al., 2010); plus, it plays an important role in aquatic ecosystem dynamics as well as in climate change (Nagai et al., 2005; Obata et al., 2009).

Given the important role that the surface ML plays in the aquatic ecosystem, the characteristics of the ML of oceans and deep lakes have been studied extensively (Hadfield and Sharples, 1996; Lehman, 2002; Rao and Schwab, 2007; Kara et al., 2009). However, the effect of variation of the MLD in large shallow lakes with strong surface mixing action has yet to be studied. Taihu Lake, for example, is often assumed to be vertically homogenous because it is a typical shallow large lake with an area of 2,338 km^2 and an average depth of approximately 2 m (Qin et al., 2004a).

Unlike deep lakes, seasonal stratification is rare in large shallow like Taihu Lake due to intensive mixing. However, Zhang et al. (2008a, 2008b) suggested that stratification may be established and maintained during daytime, and then destroyed at night; namely, diurnal stratification. Thus, large shallow lakes can also form a thin ML under appropriate conditions of wind speed/direction, water/atmosphere heat exchange, and surrounding terrain (Lövstedt and Bengtsson, 2008). The rapid establishment and destruction of stratification can lead to frequent replenishment of nutrients in the water column (Qin et al., 2004b; Pang et al., 2007; Lövstedt and Bengtsson, 2008). The mixing process can also promote algal growth under suitable conditions of MLD and photosynthetic active radiation.

In recent years, the effects of the ML on the eco-environment may be more significant with the rapid increase of air temperature, decreasing precipitation and increasing sunshine duration in the Taihu Lake region (Shang et al., 2010), but previous studies have largely focused on analyses of data measured at a single observation station (Zhang et al., 2008a, b). Moreover, high-frequency changes in wind direction and heat exchange have not been taken into account in previous studies on hydrodynamic mechanisms for Taihu Lake (Pang et al., 2008). In this context, the present work aims to provide evidence demonstrating the impact of the physical environment on aquatic ecosystems and the mechanisms underlying algal blooms with an emphasis on the spatial and temporal distribution of the surface ML in Taihu Lake.

2. Materials and methodology

2.1 *Materials*

The observation site, a station in the Global Lake Ecological Observatory Network (GLEON), is located at 31.419°N and 120.213°E in the observation plot of the Taihu Ecosystem Research Station on the southeast side of Meiliang Bay, Taihu Lake. The observation site is 150 m away from the shore and is linked to the shore through its observation trestle. The water depth was 2.33 m during the observation period. Water temperature, at depths of 0.1 m, 0.63 m, 1.1 m, 1.63 m and 2.13 m, were monitored using a TS110 water temperature chain (NexSense, USA).The meteorological parameters were monitored using a Vaisala WXT520 automatic weather system deployed above the water surface. The measured parameters included wind speed, wind direction, air temperature, relative humidity, barometric pressure and downwelling solar short-wave radiation.

The data were recorded every 10 minutes from 0500 LST 13 August 2008 to 2300 LST 18 August 2008. In this study, the data acquired at the integral time points were used. The cloud cover and evaporation level were monitored by the nearby Yixing Meteorological Station, which is 12 km from the northeast shore of Taihu Lake.

A lake-wide survey including 29 stations in Taihu Lake was conducted during 15–18 August 2008. At each station, the water samples were collected using Niskin bottles. These samples were immediately preserved at 2°C –4°C and transported to the lab for analysis within the same day. In the lab, the samples were filtered with GF/C filters (after the filters had been dried at 105°C for 4 h and preweighed), dried (105°C for 4 h) and weighed to determine the total suspended solid (TSS).

2.2 *Methodology*

2.2.1 *Water temperature simulation*

A finite-volume coastal ocean circulation model (FVCOM), which is a 3-D unstructured–grid, free-surface, primitive equation model developed by the Woods Hole Oceanographic Institution, Woods Hole, MA, USA (Chen, 2003), was used to explore the regularities and mechanisms of the temporal and spatial variation of the surface ML driven by the meteorological field in Taihu Lake. The model was set up with a triangle mesh to better fit the boundary, and its numerical calculation was configured to use the finite-volume and finite-difference methods, which provide a better representation of the mass, momentum and heat conservation in coastal and estuarine regions with complex geometry (Chen, 2003). The model was closed physically and mathematically (Chen, 2003), using the Mellor and Yamada level 2.5 turbulence closure scheme for vertical mixing and the Smagorinsky turbulence closure scheme for horizontal mixing (Chen, 2003). Horizontal and vertical turbulence diffusion coefficients were introduced as functions instead of constants to overcome the deficiencies in the previous hydrodynamic model of Taihu Lake (Qin and Fan, 2002). In addition, the bottom boundary condition for temperature in most finite-difference models is simplified to $\partial T/\partial z = 0$, which is generally sound for much of the continental shelf in coastal oceans where the bottom topography is smooth with a small gradient. In this paper, the δ-coordinate was used in the vertical direction and divided into 14 levels: 0.0 m, 0.166 m, 0.332 m, 0.498 m, 0.664 m, 0.83 m, 0.996 m, 1.162 m, 1.328 m, 1.494 m, 1.66 m, 1.826 m, 1.992 m, and 2.1528 m.

2.2.2 *Quantitative analysis of the net heat flux received by the water of Taihu Lake*

The net heat flux indicates the heat received by the water during the exchange process between water and atmosphere. Its components include net short-wave radiation flux, long-wave radiation flux, sensible heat flux and latent heat flux, and the components were analyzed quantitatively as described previously by Maggiore et al. (1998), Churchill and Kerfoot (2007) and Kim and Cho (2011).

Determination of the net short-wave radiation flux into the lake was calculated according to:

$$Q_{\mathrm{s}} = (1-\alpha)Q_{\mathrm{s0}} \tag{1}$$

where Q_{s0} represents short-wave radiation monitored using the Vaisala WXT520 automatic meteorological system, α is the albedo of the water surface, and Q_{s} is the short-wave radiation into the water (W m^{-2}).

The net long-wave radiation flux was calculated using the following formula:

$$H_{\mathrm{LW}} = \varepsilon\sigma T_{\mathrm{w}}^{4}(0.05e_{\mathrm{a}}-0.39)B_{\mathrm{c}} - 4\varepsilon\sigma T_{\mathrm{w}}^{3}(T_{\mathrm{w}}-T_{\mathrm{a}})\ , \tag{2}$$

where H_{LW} is the net long-wave radiation flux (W m^{-2}); ε is the emissivity of the water; σ is the Stephen Boltzmann constant; T_{w} and T_{a} are the temperatures (K) of the water and atmosphere, respectively; and B_{c} is the cloud correction factor, $B_{\mathrm{c}} = (1-0.72C)$, where C represents the cloud cover.

The heat influx due to sensible and latent heat was calculated as follows:

$$H_{\mathrm{sen}} = \rho_{\mathrm{a}}\zeta_{\mathrm{pa}}U\kappa_{\mathrm{sat}}(T_{\mathrm{w}}-T_{\mathrm{a}})\ , \tag{3}$$

$$H_{\mathrm{lat}} = \rho_{\mathrm{a}}L_{\mathrm{e}}U\kappa_{\mathrm{lat}}(q_{\mathrm{a}}-q_{\mathrm{sat}})\ , \tag{4}$$

where ρ_{a} represents the atmospheric density, ζ_{pa} is the atmospheric heat capacity, κ_{sat} is the transforming coefficient of sensible heat, κ_{lat} is the transforming coefficient of latent heat, q_{a} is the specific humidity, and q_{sat} is the saturation specific humidity.

2.2.3 *Determination of the mixed layer depth*

According to the optimal definition of the ML developed by Kara et al. (2000), the MLD of Taihu Lake was determined as follows:

(1) The temperature at 10 cm below the water surface was considered to be the initial reference temperature (T_{ref}) to avoid the variation caused by evaporation at the water surface;

(2) To determine the regions with similar temperature, we compared the temperatures (T_n, T_{n+1}) of the two adjacent water layers (h_n, h_{n+1}). If the difference was less than one-tenth of the standard value (0.8°C), the two layers were considered to be regions with the same temperature; thus, we continued to search deeper layers. If the difference was larger than 0.08°C, the h_n was considered as MLD.

2.2.4 *Determination of the Richardson Number*

In Taihu Lake, the inflows and outflows are small; therefore, it can be regarded as a closed lake, and the mixing effect caused by outflows and withdrawals may be omitted (Pang and Pu, 1996).

In addition to the abovementioned processes, the following also affect mixing: (1) the vertical shear of current velocity induced by wind, which leads to heat transfer to the lower layer and contributes to the mixing of the layers; and (2) heat exchange across the air–water interface (Tuan et al., 2009). The second process may have an opposite effect on the mixing. On the one hand, thermal stratification will be produced and maintained when wind is unable to mix the heated surface water over the whole water column. On the other hand, the thin MLD will become deeper or be destroyed when the net heat flux directed into the water is not large enough to cause stratification in the lake (Tuan et al., 2009). Together, these two processes determine the variation of water mixing. The Richardson Number is a measure of the relative importance of turbulence induced by wind and thermal effects in the water column. This research focused on the temporal and spatial variation of the Richardson Number to explore the spatial differences in the mechanisms controlling the MLD. We calculated the Richardson Number as follows:

The oscillation frequency (N) of stable stratification is defined as:

$$N = \sqrt{-\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}} , \tag{5}$$

where ρ_0 and ρ represent the mean and actual density of water, respectively; g is gravitational acceleration; and z is the depth of the water.

Thus, the Richardson Number (Ri) can be expressed as:

$$Ri = \frac{N^2}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} , \tag{6}$$

where u and v represent the horizontal velocity components, respectively.

2.2.5 *Estimation of the euphotic depth*

According to the relationship between the concentration of TSS and the euphotic depth of PAR [$D_{\rm eu}$(PAR)] (Zhang et al., 2006), the euphotic depths of PAR in Taihu Lake were estimated before the spatial distribution of TSS was calculated using the method of inverse distance weighted interpolation. The formula is as follows:

$$D_{\rm eu}({\rm PAR}) = \frac{4.605}{0.0626{\rm TSS} + 1.60608} . \tag{7}$$

3. Results

3.1 *Simulation and calibration of the water temperature in Taihu Lake*

As a large shallow freshwater lake, the stratification of Taihu Lake is mainly determined by the vertical temperature profile. Hence, the three-dimensional water temperature of Taihu Lake was simulated by coupling the heat exchange between the atmosphere and water with FVCOM.

In order to analyze the temporal and spatial variation of the MLD in Taihu Lake using the three-dimensional water temperature data, the result of the simulation had to be calibrated using measured water temperature data. Thus, the meteorological data described in Section 2.1 were used as the input data to simulate the water temperature during 13–18 August 2008. Finally, we interpolated the simulation results into the observation points and the depths in order to validate the simulation and analyzed the changes of the temperature vertical profile.

The variation of surface water temperature with time in the simulation was consistent with that of the measured data. There was a minimum relative error of 1.37% and a maximum relative error of 5.4% (Fig. 1), which showed that our model was suitable for the simulation of surface water temperature.

To further validate the simulated temperature results, the relationship between the simulated and measured data at various depths was analyzed and displayed in a scatter plot (Fig. 2). The results showed that these two sets of data were distributed along a straight line $y = 0.997x$, with a correlation coefficient of 0.83 (n=695). The mean relative error was 1.3%, and the maximum relative error was 6.3%. These results further confirmed that our model was suitable for the simulation of the three-dimensional water temperature of large shallow lakes.

3.2 *Error analysis*

There were two possible causes of water temperature simulation errors. First, the one-hour interval be-

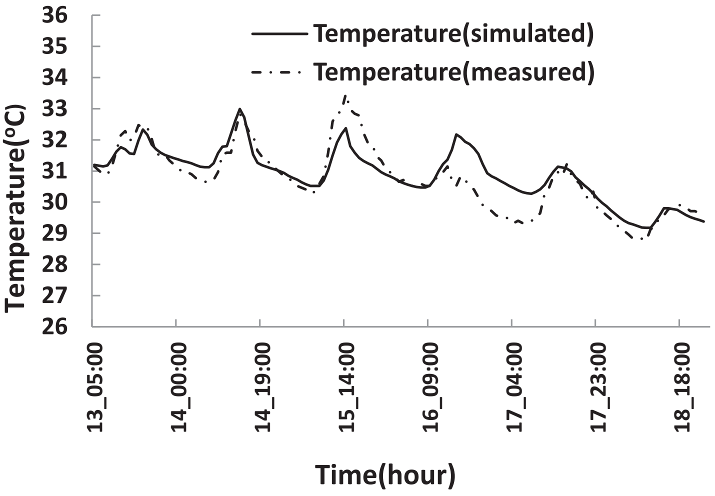

Fig. 1. Temporal variation between measured and simulated water temperature at 10 cm.

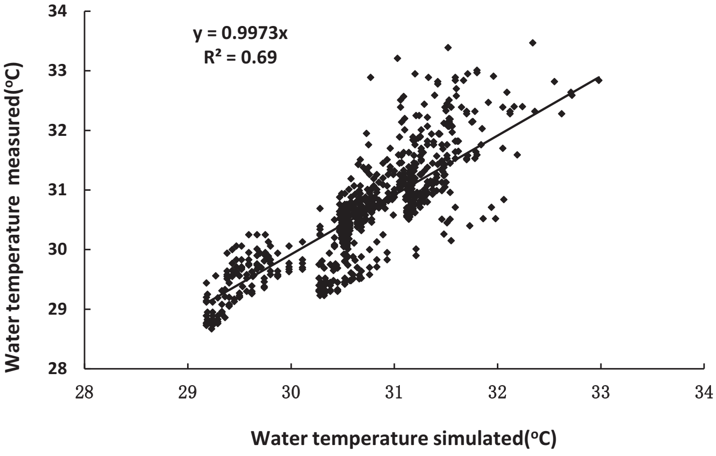

Fig. 2. Correlation between measured and simulated water temperature (n=695).

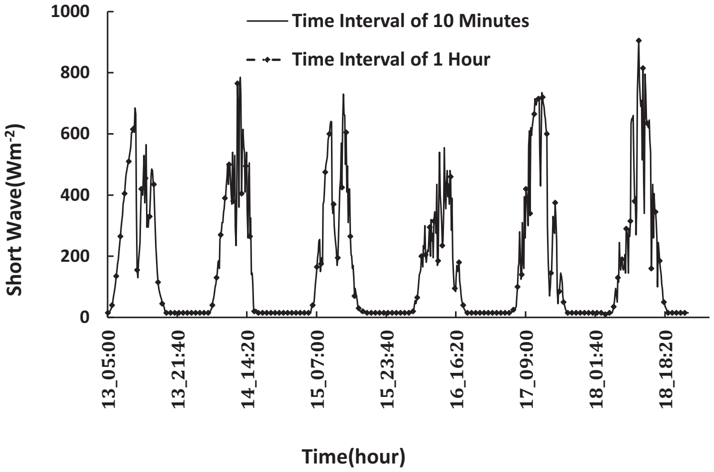

Fig. 3. Time series of short-wave radiation flux.

tween two continuous meteorological data points, such as net short-wave radiation flux, was too long to accurately depict the time series of the meteorological data. For instance, at 1300 LST 15 August, the net short-wave radiation flux value was 425 W m^{-2} lower than the measured value (730 W m^{-2}) at 1320 LST 15 August (Fig. 3). Second, the water albedo may affect the accuracy of the water temperature simulation. In our model, the albedo of the water surface was set as a constant (Gill, 1982; Guarini et al., 1997). However, it can be modified by variation in the atmospheric turbidity and solar altitude. The atmospheric turbidity impacts direct-beam irradiances, subsequently affecting the water albedo, and the solar altitude exhibits obvious daily variations (Payne, 1972). Thus, the constant might cause error in the simulation of water temperature.

3.3 *Temporal and spatial distribution of the MLD*

The factors involved in water stratification and mixing were as follows: (1) heat exchange between the water and atmosphere; and (2) the turbulence that resulted from the vertical shearing of the horizontal velocity induced by wind. In this section, we focus mainly on elucidating the influence of heat exchange on water stratification and mixing. The second factor will be discussed later, in section 4.2.

The processes of heat exchange between the water and atmosphere involves short-wave and long-wave radiation, as well as sensible and latent heat. The analysis of the time series of the heat flux components (Figs. 4–6) revealed that the fluctuation amplitude of the net heat flux directed into the lake (pos-

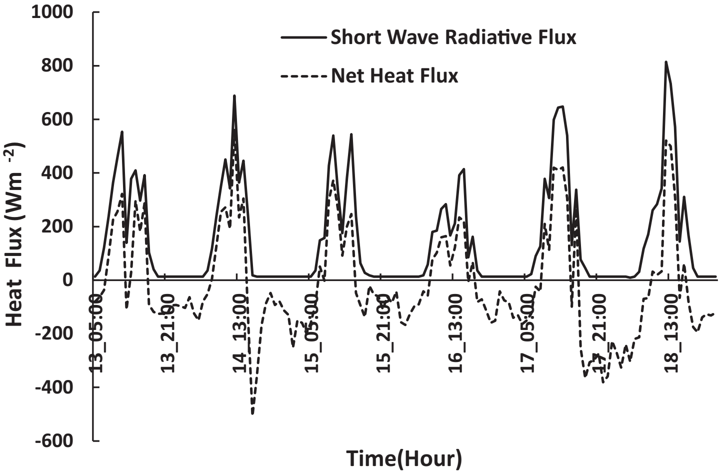

Fig. 4. Time series of net heat flux and short wave radiation flux.

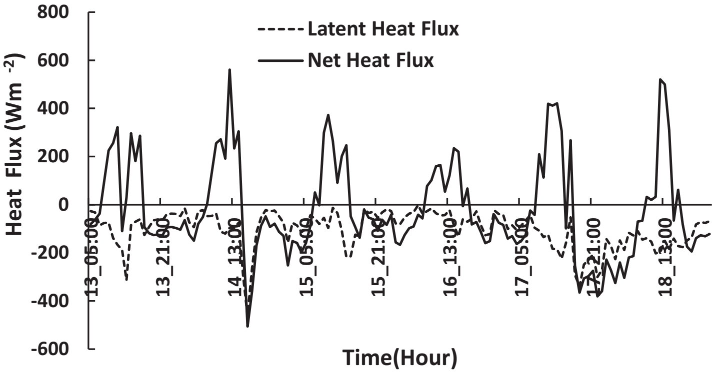

Fig. 5. Time series of net heat flux and latent heat flux.

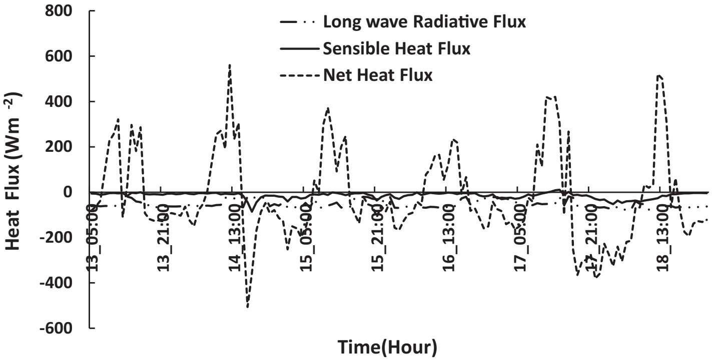

Fig. 6. Time series of net heat flux, sensible heat and long-wave radiation flux.

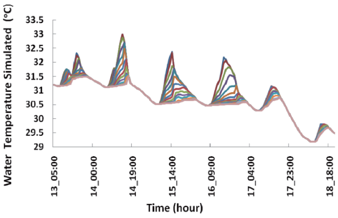

Fig. 7. Times series of water temperature at different depths.

itive) was less than the case of short-wave radiation flux; the phase of net heat flux exhibited a similar changing trend compared with short-wave radiation flux (Fig. 4), which suggested that the diurnal trend of the net heat flux was determined principally by the short-wave radiation flux when the net heat flux was positive. The sensible heat flux, latent heat flux, and the long-wave radiation flux mainly contributed negatively to the net heat flux. The variation of the negative net heat flux was consistent with that of the latent heat flux (Figs. 5 and 6), suggesting that variations of latent heat flux played a key role in the process of heat loss from the water surface.

We analyzed the strength and phase of water stratification and mixing on the basis of the temporal changes of water temperature at different depths (Fig. 7) and found that water temperature exhibited a diurnal variation. The variation was as follows:

(A) The temperature increased during daytime and decreased at night;

(B) The vertical temperature difference was relatively significant during daytime and very small at night. These results suggested that the water mixed well at night on account of the conditions being favorable for convection to prevail due to heat loss from the water surface (Anis and Singhal, 2006). During the daytime of 13–16 August, the stratification was relatively more significant than that during 17–18 August;

(C) The time of the peak temperature in the lower layer lagged behind that in the upper by 2–4 h;

(D) The water temperature dropped on 17 and 18 August and, especially on the latter of these two days, the water temperature varied little among the depths, indicating that the water was well mixed according to the optimal definition for MLD (Kara et al., 2000) and the mechanism analyses on diurnal stratification

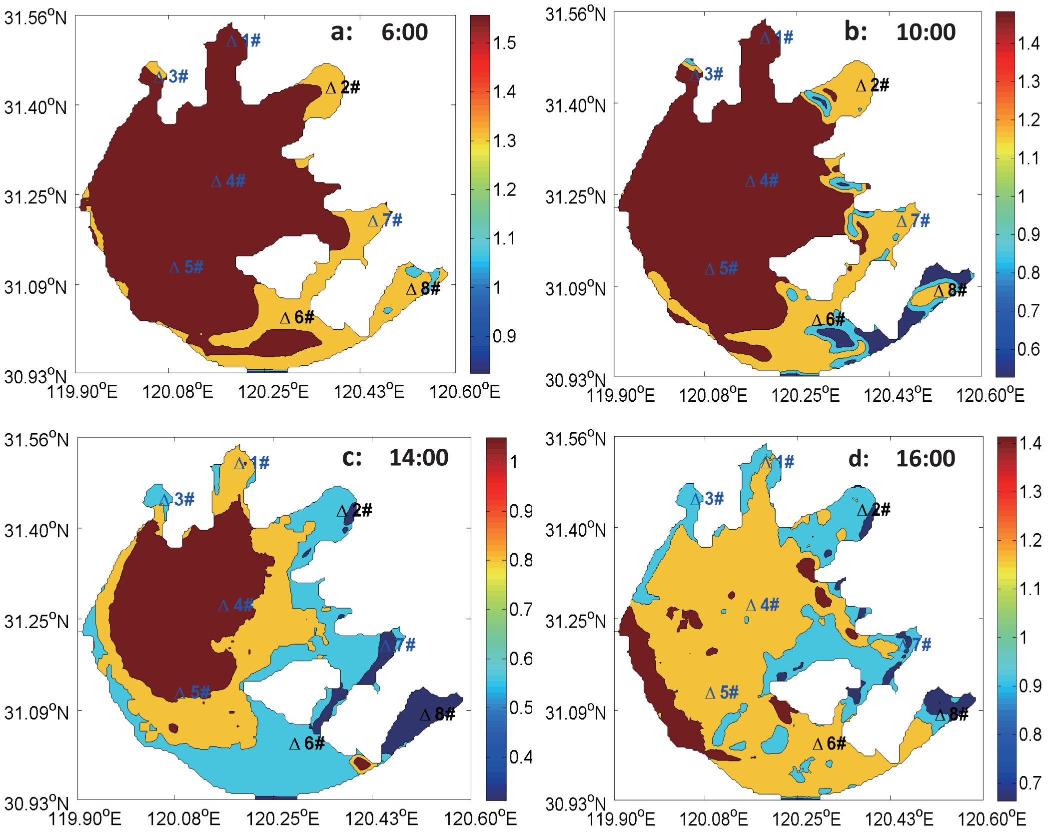

Fig. 8. Spatial distribution of MLD on 17 August 2008 at (a) 0600 LST; (b) 1000 LST; (c) 1400 LST; and (d) 1600 LST(units: m).

(Zhang et al., 2008a).

A comparison between the trends shown in Figs. 7 and 4 demonstrated that the water stratification was mainly determined by the net heat flux. When the net heat flux was positive, the water temperature increased due to receiving heat.

The data from 18 August (Fig. 4) showed that the positive net heat flux was normal, but the time span of the positive net heat flux was short. This finding suggested that the water received only a tiny amount of heat from the atmosphere, which in turn lowered the water temperature and weakened the stratification compared with that during 13–16 August. Furthermore, during the period between sunset on 17 August and sunrise on 18 August, the net heat flux exhibited a large negative value. This negative value probably indicated a great heat loss (Figs. 4–6) and showed that the atmosphere was slightly colder during this period. A north wind during this period would also contribute to this result. Together, these factors caused the water temperature to decline markedly and resulted in a strong mixing of the water column during the daytime.

The spatial distributions of the MLD were analyzed based on the MLD at 0600 LST, 1000 LST, 1400 LST, and 1600 LST, 17 August, with the sunrise at 0526 LST (Figs. 8a–d). Combined with the net latent heat flux and other processes, the water that was well-mixed at 0600 LST 17 August had started mixing from the moment the net heat flux was negative on 16 August, indicating that the ML of Taihu Lake was relatively deep (Fig. 8a). Compared with the depth of Taihu Lake (Fig. 9), the MLD was close to the bottom of the lake (Fig. 8a). As time passed, the net heat flux gradually increased. Absorption of solar radiation within a relatively thin surface layer produced thermal stratification due to the strong absorption by high-tur-

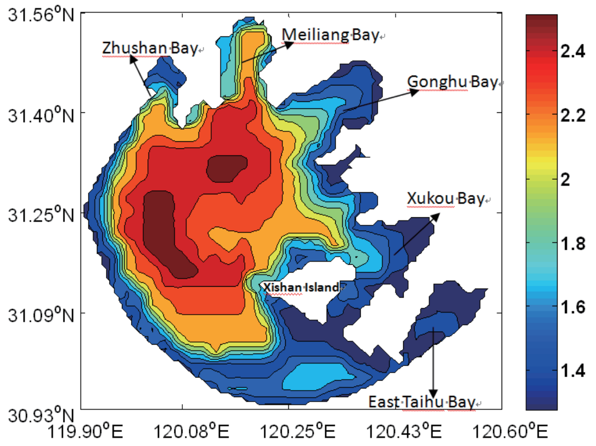

Fig. 9. Spatial distribution of water depth.

bidity water. The thermal stratification first appeared in bay regions, such as Zhushan Bay, Gonghu Bay, and Xukou Bay. The area of the relatively thin ML gradually became larger (Fig. 8b). With the short-wave radiation flux increasing and accumulating, the MLD tended to become shallower throughout the whole lake, especially in the abovementioned bay regions. The maximum MLD was less than 1 m, and the depth in the center of the lake was greater than that in other regions. From 1600 LST, the net heat flux gradually decreased; thus, the temperature difference among the different depths decreased, and the mixing process intensified. The overall MLD of Taihu Lake at 1600 LST (Fig. 8d) was greater than that at 1400 LST (Fig. 8c), and the spatial difference persisted. At all four time points, the MLD was the greatest in the center of the lake, followed by that in Meiliang Bay, the group of Zhushan Bay and Gonghu Bay, and the group of East Taihu Bay and Xukou Bay.

3.4 *Temporal variation of MLD in different lake regions*

To further analyze the temporal changes in the MLD, eight observation points (#1–8) were selected: Meiliang Bay(#1); Gonghu Bay (#2); Zhushan Bay (#3); the center of the lake (#4); the west (#5) and southwest parts of Xishan Island (#6); Xukou Bay (#7); and the East Taihu Bay (#8). Four subgraphs in Fig. 10, each consisting of two points, were employed to clearly depict the temporal changes of the MLD at these points.

In the different lake regions, the water was well mixed during the period with a negative net heat flux, especially between sunset and sunrise on the following day. The MLD was different in different regions. In Meiliang Bay, it was 1.8 m, which was 0.4 m deeper than that in Gonghu Bay. Furthermore, the MLD was 1.6 m in Zhushan Bay, which was 0.2 m shallower than that in the central lake. At the two points in west of Xishan Island, the MLD was 1.8 m and 1.4 m, respectively, while it was approximately 1.4 m in Xukou Bay and East Taihu Bay.

During the period when the net heat flux was positive, the temporal variations of the MLD in these regions were as follows: (1) In the daytime from 13–18 August, the MLD trend displayed a double valley, which was consistent with the bimodal variation in the net heat flux (Figs. 4–6; Figs. 10a–d); (2) From 13–16 August, the minimum value of MLD was similar among the different lake regions; (3) On 17 and 18 August, the MLD was significantly different among the different lake regions. The smallest depth occurred in Gonghu Bay, with values of 0.4 m and 0.6 m, followed by that in Xukou Bay and East Taihu Bay (the depths were similar: 0.5 m and 0.7 m for the two days, respectively), Meiliang Bay and Zhushan Bay (the depth on both days was 0.8 m), and the center of the lake and the western part of Xishan Island (approximately 1.2 m).

In summary, stratification disappeared at night because of hydrodynamics and the declining effect of the net heat flux. In the daytime, the establishment of stratification depended on the effect of the net heat flux. The MLD in large shallow lakes like Taihu Lake shows not only an apparent diurnal variation, but also significant spatial differences. The mechanism of stratification is complex and will be discussed in detail below.

4. Discussion

Taihu Lake exhibits significant temporal and spatial variation in its MLD. The mechanisms underlying this variation are discussed in this section.

4.1 *Mechanisms underlying the temporal variation of the MLD in Taihu Lake*

In an ocean or a deep lake in winter or summer, there is a relatively stable stratification that affects phytoplankton production, algal blooms and nutrient cycling (Sverdrup, 1953). However, the seasonal stratification may be a limiting factor for phytoplankton photosynthesis because the nutrients in the upper layer may be depleted and the stratification prevents the supplementation of nutrients from the lower layer. In large shallow lakes, diurnal stratification has a stronger impact on the ecological environment than in the ocean or deep lakes. The fact that stratification is established and destroyed quickly is beneficial to nutrient supplementation to the upper layer.

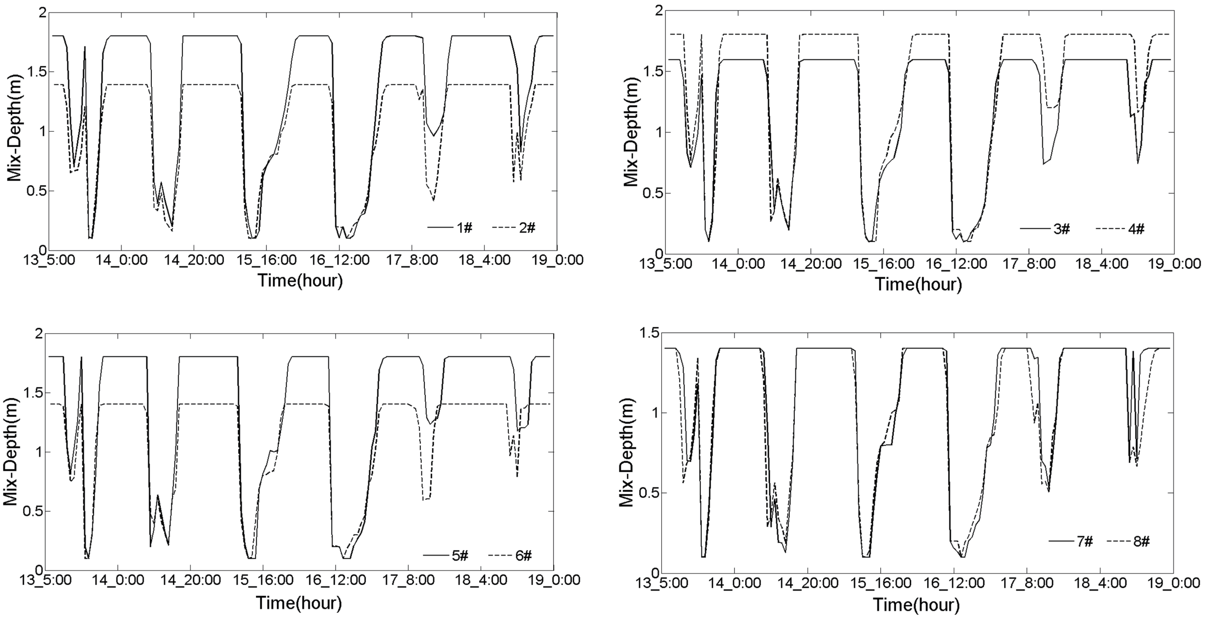

Fig. 10. Time series of MLD at different observation points.

The vertical profile of water temperature in any body of water is determined by the combined effects of solar short-wave radiation heating, water surface cooling, and wind-induced mixing. Because solar short-wave radiation reduces exponentially with an increase in water depth and strong absorption in turbid water, heating can be concentrated in a thin layer, and the vertical gradient becomes greater.

Temperature gradients will become significant and probably lead to the establishment of stratification when surface temperature increases quickly. In addition, because the quickly heated layer is thin on account of strong absorption and there is relatively strong heat loss, the stratification would be quickly destroyed during a short period when the net heat flux is negative or when the effect of mixing induced by wind is strong. It can be concluded that there may be diurnal stratification in Taihu Lake, rather than seasonal stratification, because the time span of the seasonal stratification for other lakes is comparatively long (Huang et al., 1999) compared to Taihu Lake.

In addition, there are two processes that can destroy the stable stratification after the establishment of the temperature gradient. First, the net heat loss can decrease the water temperature. As a result, the surface water temperature is reduced to form unstable conditions in which the upper water is cold while the lower water is warm, which in turn results in convective mixing and an increase in the MLD. This phenomenon may be caused by a cooling process when the net heat flux is directed out of the lake (negative) resulting from such events as a cold air break and low solar radiation, for instance, on 18 August 2008. The process of heat exchange may lead to diurnal stratification when solar heating is large enough to overcome the mixing effect induced by wind. Alternatively, the stratification could be destroyed or prevented from being established, as evidenced by the stratification and mixing phenomena monitored during 13–18 August (Figs. 7 and 10). Second, the momentum transferred from the atmosphere decreases along with an increase in water depth, so the vertical shear of the horizontal movement may lead to water mixing when it overcomes the effect resulting from the vertical temperature gradient. Additionally, mixing could arise from a combination of the vertical shear of the horizontal movement and the negative net heat flux process. As a result, the water mixing will be strengthened, which in turn can lead to the disappearance of stratification at night, or even in daytime, making it difficult to establish diurnal stratification.

Without the hydrodynamic effects, diurnal stratification can form in Taihu Lake under the heating effect of short-wave radiation. The effect of net heat flux on such diurnal stratification can be confirmed by the relationship between net heat flux and the surface MLD at all of the previously mentioned points (Table 1).

The correlation between net heat flux and surface

Table 1. Relationship between the net radiation flux and the surface MLD.

	Sample size			
point #	139	138	137	136
1#	−0.44	−0.63	−0.67	−0.59
2#	−0.55	−0.69	−0.70	−0.60
3#	−0.50	−0.66	−0.67	−0.58
4#	−0.41	−0.58	−0.62	−0.55
5#	−0.40	−0.57	−0.62	−0.56
6#	−0.50	−0.63	−0.61	−0.50
7#	−049	−0.63	−0.65	−0.56
8#	−0.58	−0.71	−0.70	−0.58

MLD, as well as their temporal relationship, is shown in Table 1. By comparing the correlation coefficients between net heat flux and the MLD with a 0-hour delay (n=139), 1-hour delay (n=138), 2-hour delay (n=137), and 3-hour delay (n=136) respectively, we found that the MLD with a 2-hour delay exhibited the best correlation with net heat flux data for all of the lake regions. These results not only verified that net heat flux was the driving force for the establishment of diurnal stratification, but also showed that the variation of net heat flux was prior to the change of the MLD.

4.2 *Mechanisms underlying the spatial variation of the MLD in Taihu Lake*

The effects of thermodynamic processes on the establishment of the thin ML only illustrated how energy influenced the vertical distribution of water temperature; they could not explain the spatial variation in the MLD mentioned previously (Table 1, Figs. 8 and 10). Here, we address this question in detail.

Taihu Lake is defined as a large shallow lake based on the ratio between its area and depth, which covers approximately 50×60 km^2, so the atmosphere over the area is approximately uniform horizontally, and the net heat flux is almost even for the whole lake. However, the flow field of water exhibited significant spatial heterogeneity because it depended on the fetch length, duration and water depth. Hence, the spatial difference in the three-dimensional flow field may be the only cause that led to the spatial variation of the MLD.

The transfer of momentum from the air to the water causes the vertical shear of the horizontal current in the lake. Only when such an effect is greater than the buoyancy resulting from stable stratification will the turbulent mixing of surface water appear. Combined with the relatively weak temperature stratification in Taihu Lake, the turbulent mixing of surface water can result in a weakening or rapid disappearance of diurnal stratification and an increase in the MLD. The Richardson Numbers at different points of Taihu Lake were determined using the method described above (Fig. 11), and they were calculated based on the upper five layers of water where the difference in water temperature was relatively significant.

The Richardson Number can decrease with increasing vertical shear of horizontal velocity or decreasing vertical stratification of the density. Hence, the temporal and spatial variation of the Richardson Number can account for the mechanically and thermodynamically driven variation in the surface MLD in Taihu Lake.

The temporal variation in the Richardson Number at different points showed that when net heat flux was positive, the Richardson Numbers in Gonghu Bay, Zhushan Bay, Xukou Bay, East Taihu Bay, Meiliang Bay, and the southwestern part of Xishan Island were greater than those in the center of the lake, indicating that the water in these former regions was easily stratified (Fig. 11; each subgraph contains the Richardson Numbers at two points). During diurnal stratification, the MLD in the lake centre was relatively deeper than those in other regions, which was consistent with the results of Figs 8a–d. However, in the center of the lake, the Richardson Number was small, suggesting that the strong disturbance caused by the shear of the horizontal flow field tended to mix the water. In addition, because this study was performed in summer when there were predominantly southerly and northerly winds (Fig. 12), the wind-driven effects were relatively apparent in Meiliang Bay. Thus, the Richardson Number in Meiliang Bay was small and

Table 2. The mean Richardson Number during the simulation.

point #	mean Richardson number
#1	0.291
#2	1.063
#3	1.865
#4	0.191
#5	0.185
#6	0.244
#7	0.651
#8	0.523

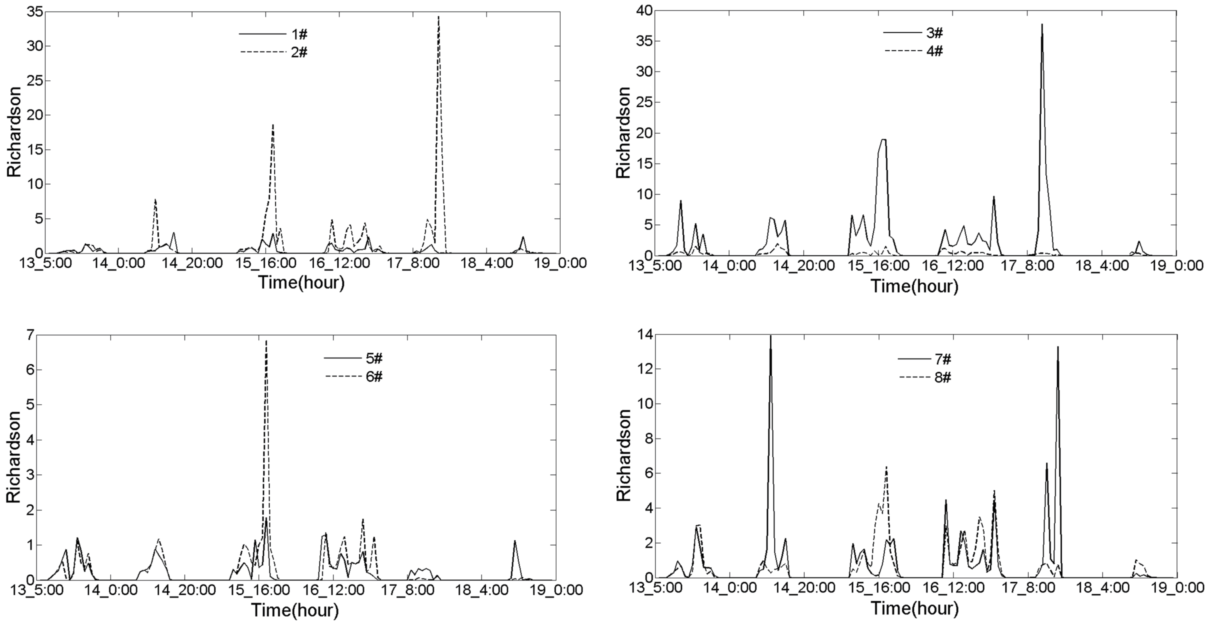

Fig. 11. Time series of the Richardson number in different regions of Lake Taihu.

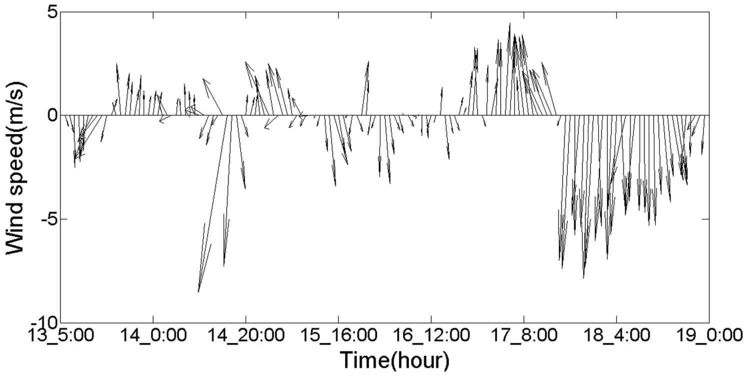

Fig. 12. Time series of wind speed and wind direction.

Table 3. The relationship between the Richardson Number and the MLD.

point #	Correlation coefficient (n=139)
#1	−0.53
#2	−0.28
#3	−0.41
#4	−0.57
#5	−0.53
#6	−0.40
#7	−0.33
#8	−0.51

there was relatively strong mixing action. On 18 August, due to the short duration of the positive net heat flux and subsequently tiny energy received, the water in Meiliang Bay tended to mix uniformly and showed a small Richardson Number, which was consistent with our previous analysis (Fig. 11 and Table 2).

We further confirmed that the Richardson Number could represent changes in turbulence through a correlation analysis between the MLD and Richardson Number at the different points mentioned previously (Table 3).

4.3 *Analysis of the effect of the mixing process on algal production*

Algal development is thought to be strongly influenced by surface irradiance, vertical mixing and temperature (Tirok and Gaedke, 2007). The effect of the ML is more prevalent than the effect of temperature because the ML governs both the light climate and temperature in the ML (Berger et al., 2007). In addition to temperature, the turbulence of the ML controls the vertical movement of algae, which in turn affects algal production and destruction by controlling the light climate. Therefore, the ratio between the euphotic depth and the MLD is one of the major factors affecting the growth rate of algae (Sverdrup, 1953). The favorable physical conditions for algal production is a deep euphotic depth and a thin ML regardless of the effect of nutrients, temperature, and so on.

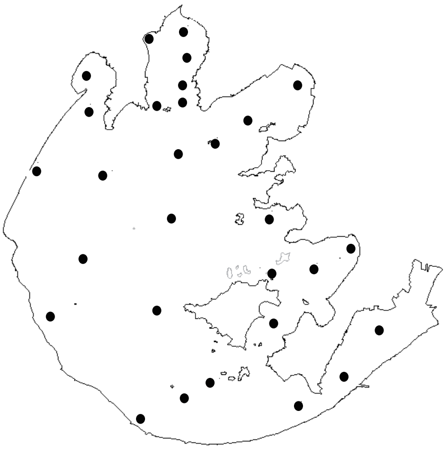

Fig. 13. Location of sampling stations.

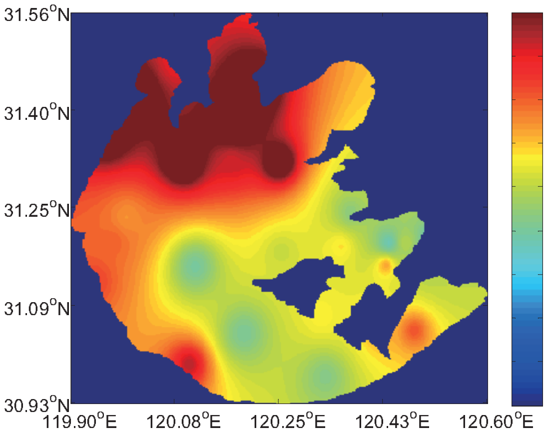

Fig. 14. Spatial distribution of euphotic depth on 15 August 2008 (Units: m).

Based on the concentrations of TSS at 29 sampling stations in Taihu Lake (Fig. 13), during 15–18 August 2008, the euphotic depths were estimated. The euphotic depths in Meiliang Bay and Zhushan Bay were relatively deep Compared to other regions (Fig. 14). In contrast, the MLDs in the bays, such as Zhushan Bay, Gonghu Bay and Meiliang Bay, were relatively shallow. The ratio between the MLD and euphotic depth in Zhushan Bay and Meiliang Bay met the favorable conditions for algal production, but it needs to be further validated by future observations.

5. Conclusion

In summary, owing to heat exchange between the water and atmosphere through short-wave radiation, long-wave radiation and sensible and latent heat, Taihu Lake is able to establish diurnal stratification and maintain a thin surface ML during periods when net heat flux is large. The variation of the MLD was found to be well correlated to net heat flux with a two-hour delay. Under the effects of hydrodynamic and thermodynamic forces, the MLD exhibited apparent spatial variation. Specifically, the thin ML was established and maintained more easily in Gonghu Bay, Zhushan Bay and East Taihu Bay compared to Meiliang Bay. However, compared with the center of the lake it formed more easily in Meiliang Bay. It was relatively difficult for diurnal stratification to be established in the center of the lake because the mechanical effects are very strong in this region, which in turn results in a strong mixing action and a greater MLD. The spatial differences in hydrodynamic action are probably the major cause of the spatial variation in the MLD in Taihu Lake. The ratio between the MLD and euphotic depth in Meiliang Bay and Zhushan Bay is favorable for algal production.

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