Diurnal and Seasonal Variations of Thermal Stratification and Vertical Mixing in a Shallow Fresh Water Lake

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ABSTRACT

Among several influential factors, the geographical position and depth of a lake determine its thermal structure. In temperate zones, shallow lakes show significant differences in thermal stratification compared to deep lakes. Here, the variation in thermal stratification in Lake Taihu, a shallow fresh water lake, is studied systematically. Lake Taihu is a warm polymictic lake whose thermal stratification varies in short cycles of one day to a few days. The thermal stratification in Lake Taihu has shallow depths in the upper region and a large amplitude in the temperature gradient, the maximum of which exceeds 5°C m^{-1}. The water temperature in the entire layer changes in a relatively consistent manner. Therefore, compared to a deep lake at similar latitude, the thermal stratification in Lake Taihu exhibits small seasonal differences, but the wide variation in the short term becomes important. Shallow polymictic lakes share the characteristic of diurnal mixing. Prominent differences on the duration and frequency of long-lasting thermal stratification are found in these lakes, which may result from the differences of local climate, lake depth, and fetch. A prominent response of thermal stratification to weather conditions is found, being controlled by the stratifying effect of solar radiation and the mixing effect of wind disturbance. Other than the diurnal stratification and convection, the representative responses of thermal stratification to these two factors with contrary effects are also discussed. When solar radiation increases, stronger wind is required to prevent the lake from becoming stratified. A daily average wind speed greater than 6 m s^{-1} can maintain the mixed state in Lake Taihu. Moreover, wind-induced convection is detected during thermal stratification. Due to lack of solar radiation, convection occurs more easily in nighttime than in daytime. Convection occurs frequently in fall and winter, whereas long-lasting and stable stratification causes less convection in summer.

Key words: Lake Taihu, thermal stratification, solar radiation, wind speed, convection

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1. Introduction

In many studies of lake temperature, thermal stratification in the body of a lake has attracted widespread attention. Thermal stratification is a stable state in lakes that circumscribes the vertical transport of oxygen and other dissolved gases, limiting the supply of nutrients for aquatic organisms (Schadlow and Hamilton, 1995). Plankton can be trapped in the surface layer where sunlight is abundant, which increases the risk of water quality problems such as algal blooms (Berger et al., 2007; Fonseca and de M. Bicudo, 2008). The stability of

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thermal stratification changes the chemical properties of the water body by affecting the exchange of chemical elements between sediment and the water column (Giles et al., 2016). The thermal structure of a lake not only indicates the response of the lake to atmospheric forcing (Oswald and Rouse, 2004) but also plays an important role in changing the wind and fluxes to the atmosphere by controlling surface temperature (Liu et al., 2015), and therefore can be a useful variable for improving numerical weather forecasts (Heo and Ha, 2010).

The geographical position and depth of a lake directly influence its vertical temperature distribution. Simultaneously, the thermal stratification is controlled by several external factors (Churchill and Kerfoot, 2007). For instance, salinity, specific heat, algal blooms, turbidity, heat flux, and meteorological elements all contribute to the characteristics of vertical temperature profiles (Fee et al, 1996; Condie and Webster, 2002; Zhao et al., 2011; Wang et al., 2012; Wang et al., 2014). For most deep lakes in the temperate zone, greater heat storage leads to sustained stability, which causes the temperature to vary over a long cycle (Kalff, 2002). Hence, although the general characteristics of temperature change in deep lakes is affected by wind disturbances, biological disturbances, and salinity (Wang et al., 2014), temperature changes are primarily due to seasonal differences in solar radiation, that is, the dimictic type and the warm monomictic type. In these two situations, a dimictic lake shows a strong thermocline in the summer, a frozen surface layer in the winter, and a homogeneous temperature in the spring and fall, which is caused by overturning. A warm monomictic lake shows only one overturning period between the fall and the spring, and no ice cover exists in the winter (Kalff, 2002; Wang et al., 2012). In shallow lakes, the heat storage is not large enough to maintain thermal stratification for more than 24 h (Kalff, 2002), which leads to rapid changes in the thermal structure. In this process, meteorological elements, heat transport at the surface, accumulation of algae, and the height of submerged plants are more influential (Zhao et al., 2011; Cheng et al., 2016). Generally, vertical mixing occurs in shallow lakes at nighttime (Deng et al., 2013). As the change in depth greatly influences the variation in thermal stratification as well as its response to different factors, the pattern of stratification in shallow lakes must possess particular characteristics.

To date, studies of the characteristics of thermal stratification and the relevant physical and chemical processes in deep lakes are relatively mature (Michalski and Lemmin, 1995; Crawford and Collier, 1997; Boehrer and Schultze, 2008; Pernica et al., 2014). Current research on similar topics in shallow water involve mainly model simulations (Chu and Soong, 1997; Farrow and Stevens, 2003), analyses of short-term cases (Tuan et al., 2009; Zhao et al., 2012), mechanisms related to internal waves (Samal et al., 2008), the vertical circulation that emerges during upwelling (Godo et al., 2001; Condie and Webster, 2002), and the regulation of entrainment in a mixing water body (Chai and Kit, 1991; Tuan et al., 2009). However, studies based on long-term data (longer than one year) to characterize features of thermal stratification in shallow lakes are still limited.

It is important to quantify the strength of stratification by determining the mixed layer depth (MLD). The MLD can be used to support the parameterization of surface-air exchanges processes in lakes (Sun et al., 2007). Field observations allow the performance of the MLD parameterizations to be validated.

At present, there are two most practical techniques for determining the MLD: the subjective method and the objective method. The former commonly involves the difference criterion and the gradient criterion (Chu and Fan, 2011), which are concise and effective, with an empirically given threshold that varies with the environment of the lake. Thus, an optimal solution in the subjective method is rarely found (Monterey and Levitus, 1997). The latter commonly involves the curvature criterion, which demands high vertical resolution because it calculates the second derivative of the water thermal property. Noisy data should be avoided when using the objective method (Chu and Fan, 2011). Kara et al. (2000) proposed an optimal definition that can process temperature profiles with low resolution and, to some extent, solves the problem in selecting a best threshold after a rigorous comparison between two independent datasets. Another novel criterion called the maximum angle method, proposed by Chu and Fan (2011), leads to good results by seeking the MLD based on profile angles. However, that method has a stringent requirement for vertical resolution.

All of the existing criteria for determining the MLD have their own advantages and limitations. A simplified form of Kara's optimal definition was used in a shallow lake for a few days in the summer, and a significant variation in the MLD was obtained (Zhao et al., 2012). However, whether it can be applied to long-term research in Lake Taihu still needs confirmation.

Lake Taihu is located in the urban agglomeration in the Yangtze River Delta, which has a dense population. Lake Taihu is not only an important source of water and food supply but also affects the surrounding weather (Zhang et al., 2017). The lake area is 2400 km^2, and the mean depth is 1.9 m, with the northwest part deeper (approximately 2.5 m) and the east part shallower (approximately 1.5 m; Qin et al., 2007; Lee et al., 2014). This study is performed based on one year observed data in Lake Taihu. The following three scientific problems are discussed. (1) How does water temperature in Lake Taihu vary diurnally and vertically in different seasons? How does the water temperature respond to various weather characteristics? (2) How should the thermal stratification in Lake Taihu be quantified? Furthermore, what are the main factors that control it? How does the thermal stratification in Lake Taihu typically change with these dominant factors under different conditions? (3) As Lake Taihu is shallow, what mechanism underlies the switch of its thermal stratification (from being stable to being unstable)?

The paper is organized as follows. Section 2 introduces the observations from the Lake Taihu Eddy Flux Network in 2015 and associated data quality control, together with the method used to determine the MLD of the lake. Section 3 presents the data analysis results, with the thermal structure and stratification of the lake and wind-induced convection being extensively discussed. Finally, conclusions are provided in Section 4.

2. Data and methods

2.1 *Sites and instruments*

The data used here are from the Pingtaishan (PTS) site in the Lake Taihu Eddy Flux Network in 2015 (Fig. 1). This site was established in June 2013 and is located close to the center of the lake (31.2323°N, 120.1086°E) with an average water depth of 2.8 m. The represented water area is mesotrophic (Lee et al., 2014) with relatively little photosynthetic activity (Hu et al., 2011). Macrophytes are not common in this zone and are omitted in our research.

The Lake Taihu Eddy Flux Network mainly includes the eddy covariance (EC) system, a four-way net radiation observation system, an automatic weather station, and a water temperature gradient observation system (Fig. 1). At the PTS site, the automatic weather station consists of an air temperature and humidity probe (model HMP155A; Vaisala, Inc., Helsinki, Finland) and an anemometer and wind vane (model 05103; R M Young Company, Traverse City, Michigan). A four-way net radiometer (model CNR4, Kipp & Zonen B. V., Delft, the Netherlands) systematically measures incoming and outgoing radiation. The water temperature gradient observation system comprises a group of temperature probes (model 109-L, Campbell Scientific) set at 0.2, 0.5, 1.0, and 1.5 m below the surface and in the sediment beneath the water column. All the data noted above are recorded at 1 Hz and processed to average values over 30 min by a data logger (model CR1000, Campbell Scientific).

Moreover, the historical meteorological data from the Dongshan weather station (approximately 36 km from the PTS site) are adopted to combine the analysis with specific weather features. The weather is classified into clear days (cloud amount ⩽ 3), overcast days (cloud amount ⩾ 8), and cloudy days (3 < cloud amount < 8; Qiu, 2013).

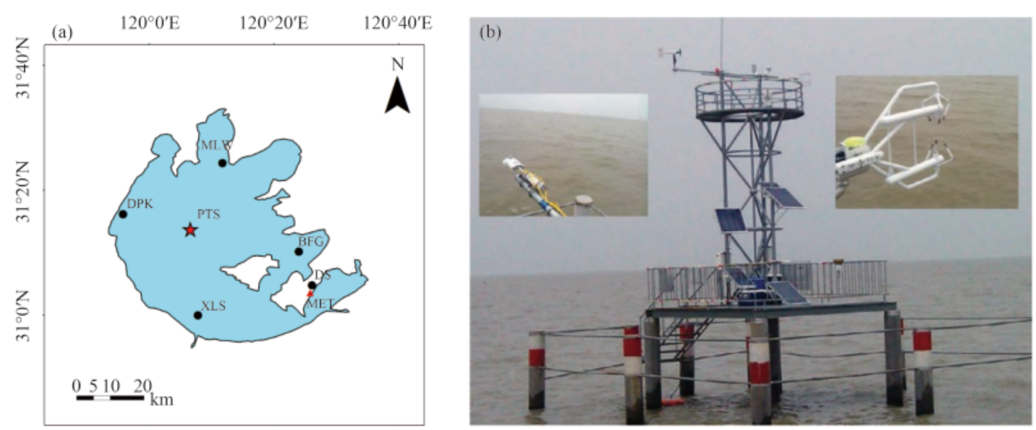

Fig. 1. (a) The location of the Lake Taihu Eddy Flux Network and (b) the instrument platform of the Pingtaishan (PTS) site. The red star marks the PTS site, and the black dots mark the Meiliangwan (MLW), Dapukou (DPK), Bifenggang (BFG), Dongshan (DS), and Xiaoleishan (XLS) sites. The Dongshan weather station (31°04′N, 120°26′E) marked by the red triangle is distinguished from the DS site. In addition to the automatic weather station and EC system mounted at 8.5 m, a four-way net radiometer and rain gauge are installed. Water temperature probes are set below the surface (Lee et al., 2014).

2.2 *Data quality control*

The data chosen from 1 January to 31 December 2015 consist of air temperature, wind speed, water vapor pressure, upward and downward longwave and shortwave radiation, and the water temperature profile. Data quality control methods are used to ensure good data quality. A comparison of five temperature probes at the same depth is performed periodically to obtain systematic errors. Periods of instrument failure, recorded on the field maintenance log, are excluded from post-field processing (Wang, 2014). High failure rates appear in May, June, August, and September. In detail, only 58% of data in May are in good quality, and this proportion is 70% in June. The water temperature probes failed completely in August, and all profile data were rejected accordingly. This problem was not fixed until mid-September, which inevitably caused the percent of passable data to be 43%. Except for the periods noted above, the data quality in other months is good.

To ensure that qualified data represent the features for the entire year, our investigation is performed with data from January, April, July, and October, which represent the seasonal features of winter, spring, summer, and fall, respectively. The quality of the data of air temperature, water vapor pressure, radiation, and wind speed is very good. Only a few small gaps in air temperature data are filled by linear interpolation. Gaps in radiation data are filled by the observations from other sites. Gaps in wind speed data are filled by measurements from the EC system at the PTS site. Those data from the EC system during the period from 30 min before precipitation to 30 min after precipitation are rejected.

2.3 *Method to determine mixed layer depth*

As a fresh-water body with extremely low salinity, Lake Taihu forms no barrier layer that indicates the difference between the isothermal layer depth (ILD) and the mixed layer depth (MLD) (Sprintall and Tomczak, 1992). Thus, adopting a temperature-based criterion to determine the MLD is convenient and reasonable. As objective methods require high vertical resolution in the profile, subjective methods are more suitable to the observation system in the Lake Taihu Eddy Flux Network. Two subjective methods, Kara's optimal definition and the traditional difference criterion, are compared to determine the more applicable one.

Based on a subjectively determined temperature difference ΔT, Kara's optimal definition searches the mixed region, where the temperature difference between adjacent layers is less than $0.1\Delta T$, downward with a continuously resetting reference temperature $T_{\rm ref}$. The MLD will be the depth where the temperature has changed by an absolute value of ΔT from $T_{\rm ref}$. This method adapts well to various stratifications in oceans (Kara et al., 2000). In our profile system, we set the initial $T_{\rm ref}$ to be the temperature at the depth of 0.2 m.

Based on the traditional difference criterion, $T_{\rm ref}$ is always the surface temperature. Therefore, the MLD with a temperature $T_{\rm b}$ lower than the surface temperature by ΔT can be determined accurately between depth intervals as calculated in Eqs. (1) and (2) below. If no depth is found for the MLD, it is set to the maximum depth, which is also applied in the optimal definition.

$$T_{\rm b} = T_{\rm s} - \Delta T, \tag{1}$$

$$\text{MLD} = \frac{T_{\rm b} - T_n}{T_{n+1} - T_n}(h_{n+1} - h_n) + h_n, \tag{2}$$

where $T_{\rm s}$ refers to the surface temperature and is represented by the temperature at 0.2 m depth, and T_n and h_n are the temperature and depth of layer n, respectively. According to Kara et al. (2000), three values of ΔT—0.8, 0.5, and 0.2°C—are used in both criteria.

The Kara's optimal definition, which performs well for oceans, gives two types of unreasonable MLD results when processing weak and thin inversion layers at the surface (Fig. 2). First, taking the period 20–28 July as an example, when the temperature difference of the inversion layer is smaller than ΔT, the algorithm is unable to find a place for $T_{\rm b}$ as the lower part of the lake is still stratified. As a result, the MLD is improperly set to the maximum depth, leading to a lack of MLD continuity in time. Second, the temperature difference of the inversion layer is slightly larger than ΔT from 4 to 8 October. This result causes a low value of MLD although vertical mixing is still quite strong in the whole water column.

Therefore, although Kara's optimal definition is a relatively comprehensive method to determine the MLD, the traditional difference criterion gives more stable results for Lake Taihu and is more suitable to use with better continuity and fewer errors.

As the MLD also varies with the value of ΔT, an appropriate ΔT should be ensured to objectively analyze the variation trend of thermal stratification. In the difference criterion, the MLD generally decreases as a lower ΔT is chosen (Fig. 2). In some cases, we find that thermal stratification (MLD < maximum depth) does not appear with ΔT = 0.5°C or ΔT = 0.8°C, but occurs only when ΔT = 0.2°C. These typical cases are included in Fig. 3 where weak thermal stratification, as a transition between stable and unstable state, is highlighted by using ΔT = 0.2°C.

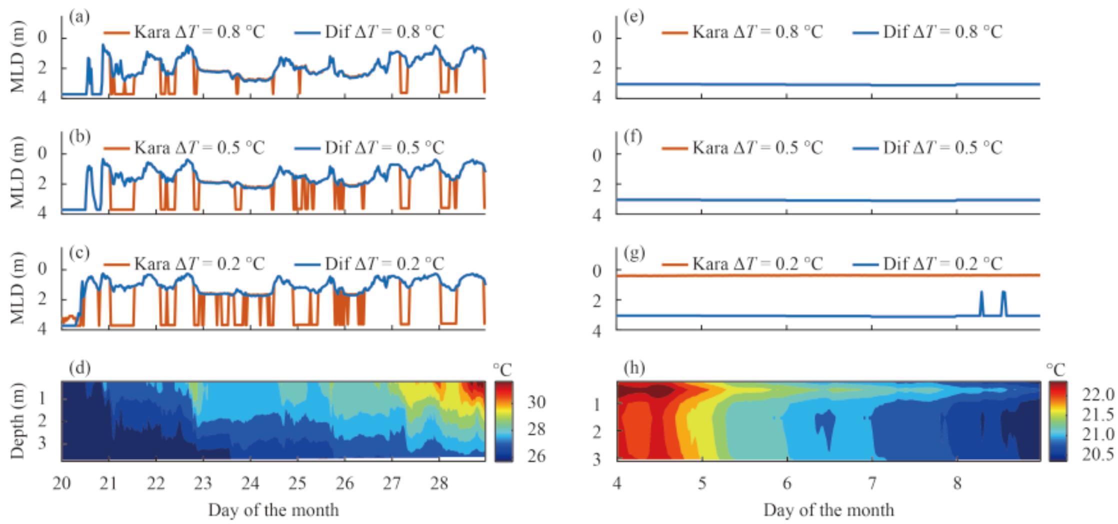

Fig. 2. Two typical differences between Kara's optimal definition and the traditional difference criterion. The left panels show the MLD of the two methods from 20 to 28 July, with ΔT set to (a) 0.8°C, (b) 0.5°C, (c) 0.2°C, and (d) the coupled water temperature. The right panels show the MLD of the two methods from 4 to 8 October, with ΔT set to (e) 0.8°C, (f) 0.5°C, (g) 0.2°C, and (h) the coupled water temperature. In the legend, the letters "Kara" and "Dif" refer to the MLDs from the optimal definition and the difference criterion, respectively. The single blue line in (e, f) indicates that equal values are determined by the two methods.

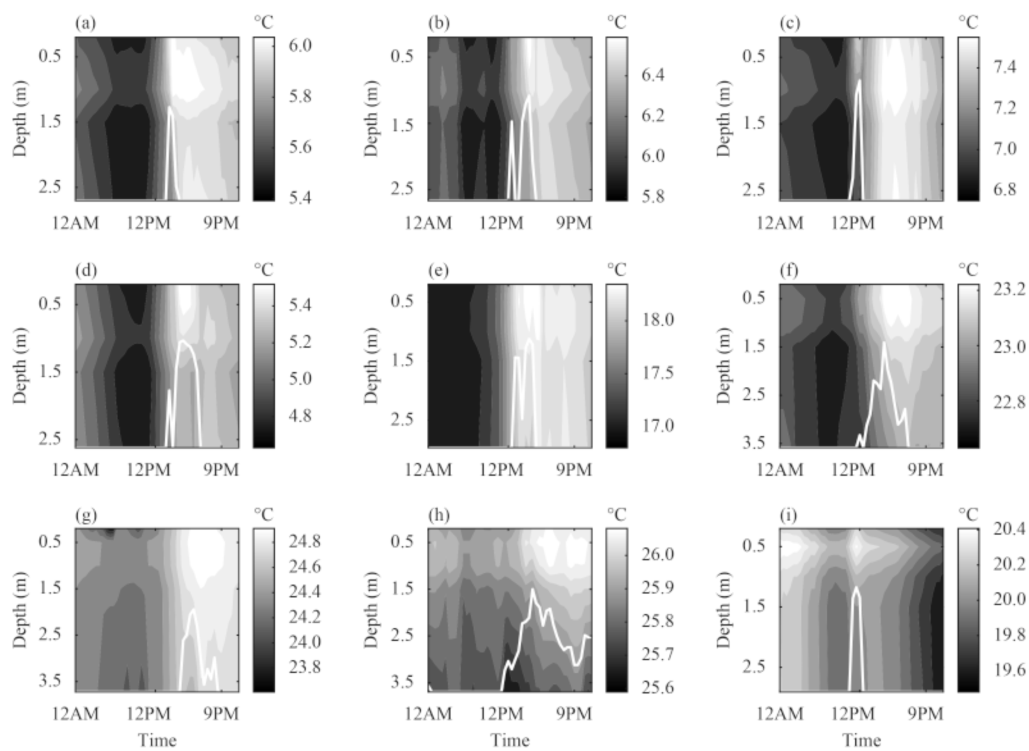

Fig. 3. Cases of water temperature and the MLD partly chosen from the daily patterns in which the wholly mixed state is shown with ΔT = 0.8°C and ΔT = 0.5°C, while thermal stratification is found with ΔT = 0.2°C, on (a) 3, (b) 9, (c) 21, (d) 31 January, and on (e) 2 April, (f) 8 July, (g) 12 July, (h) 18 July, and (i) 28 October. The white line indicates the coupled MLD at ΔT = 0.2°C.

Thus, using ΔT = 0.2°C helps to detail the change process of thermal stratification quantitatively.

Eventually, the traditional difference criterion with ΔT = 0.2°C is applied in studying thermal stratification and vertical mixing processes in Lake Taihu.

3. Results and discussion

3.1 *General characteristics of thermal stratification*

In terms of seasonal differences (Fig. 4), the thermal stratification in the spring (April) is stronger than that in the winter (January), which can be summarized by comparing the vertical temperature difference in these two months. Strong thermal stratification appears in the summer (July) with a temperature gradient that stretches to the bottom and lasts for more than 24 h (21–29 July). This effect probably results from strong solar radiation in the summer and the sustained transport of heat flux at the surface, which allows continuous accumulation of energy in the lake for a few days. In the fall, thermal stratification becomes weaker compared with that in other seasons. Although thermal stratification typically changes on a diurnal scale in Lake Taihu, some seasonal differences can still be found as a result of seasonal variations in solar radiation.

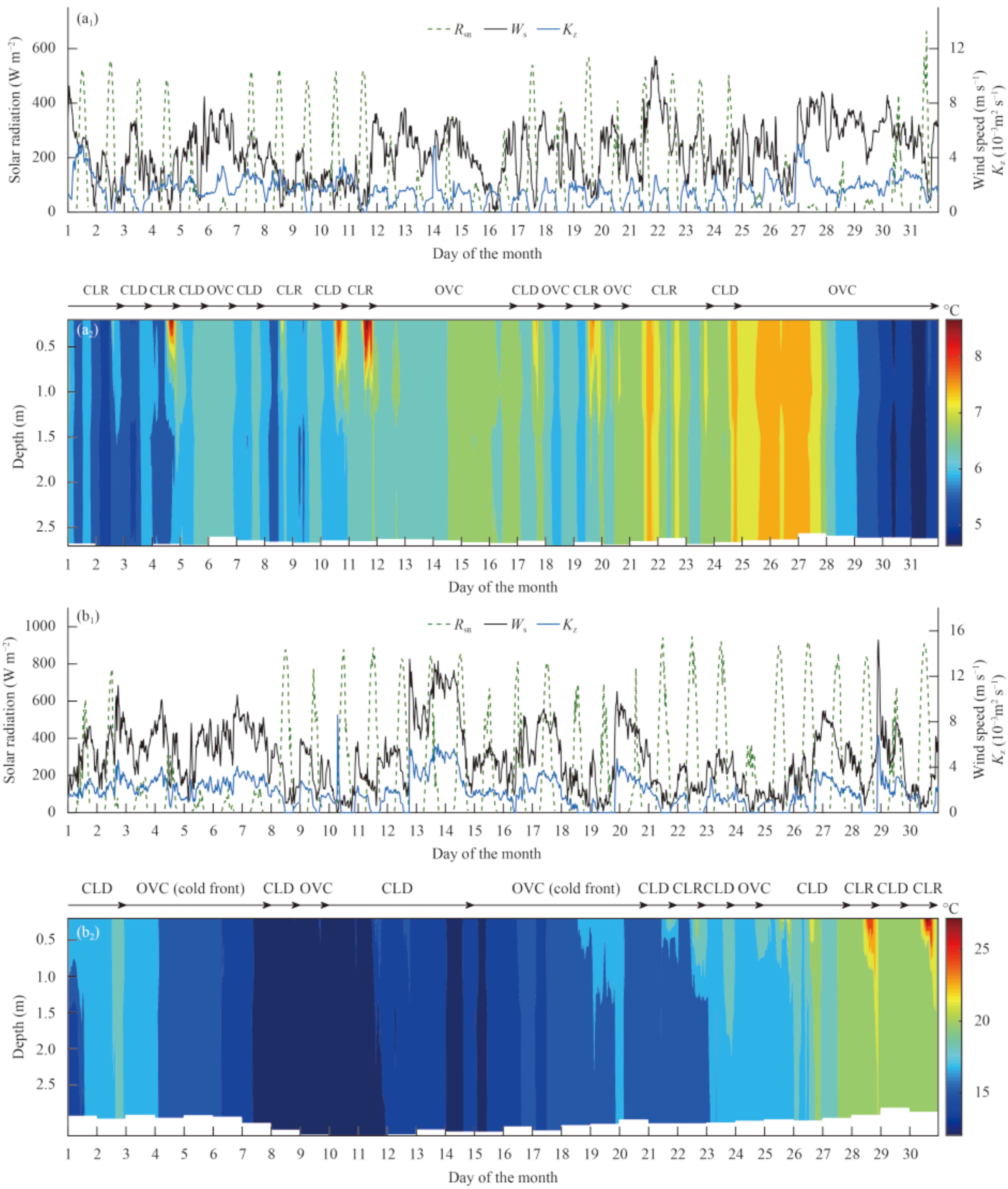

Fig. 4. Continued on next page.

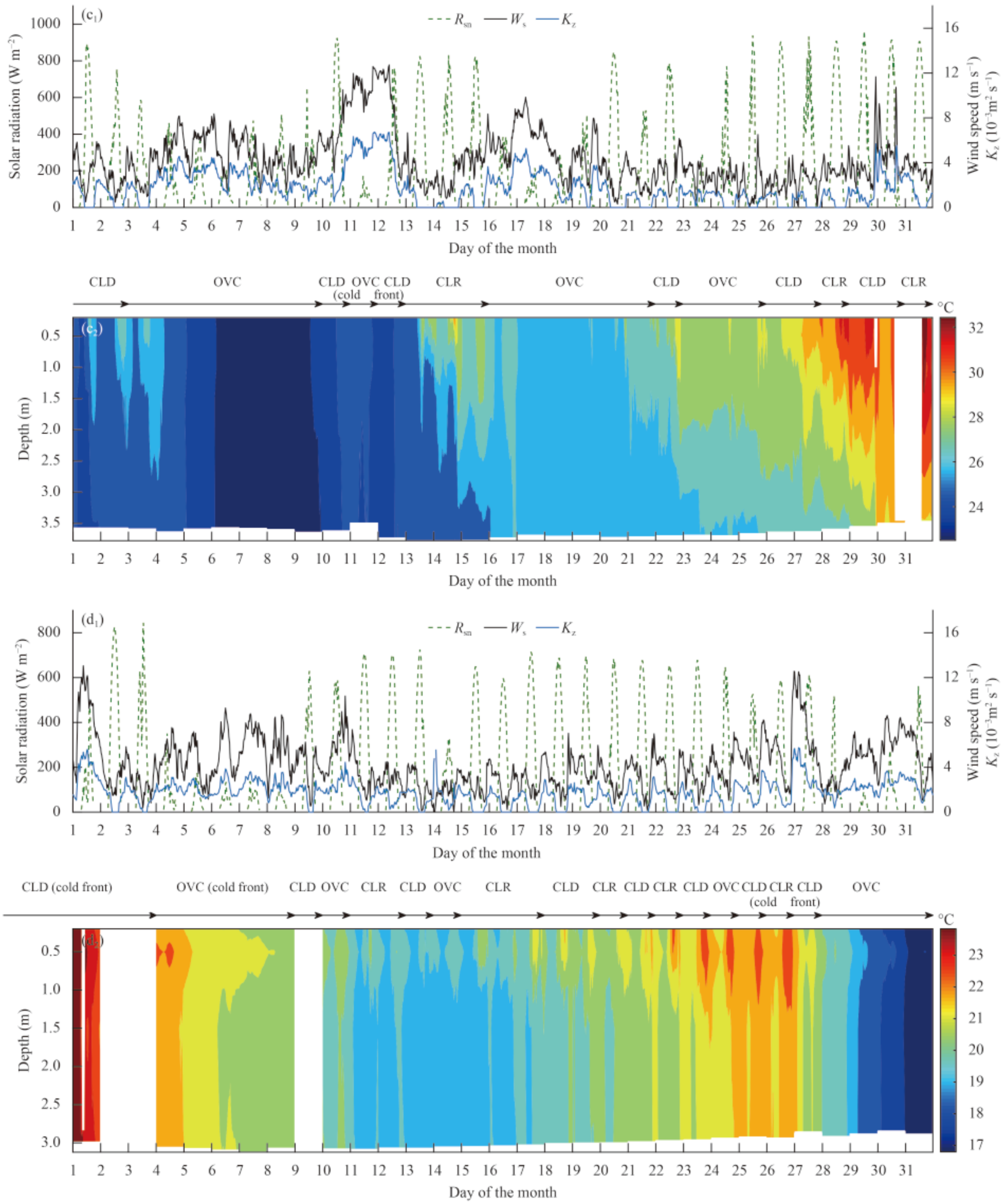

Fig. 4. (a_1, b_1, c_1, d_1) Temporal evolutions of solar radiation (R_{sn}, net shortwave radiation), wind speed (W_s), and turbulent diffusivity (K_z); and (a_2, b_2, c_2, d_2) vertical distributions of water temperature in (a_1, a_2) winter (January), (b_1, b_2) spring (April), (c_1, c_2) summer (July), and (d_1, d_2) fall (October). The accompanying dominant weather characteristics are marked with black arrows and text: CLR, CLD, and OVC denote clear days, cloudy days, and overcast days, respectively. (Overcast or cloudy days are usually associated with weather systems such as cold fronts and typhoons, which bring precipitation and strong wind as well).

The differences in stratification and mixing between shallow lakes and deep lakes can be shown on comparing Lake Taihu to a deep lake at similar latitude. Deep lakes commonly mix less frequently than shallow lakes. The type of mixing regime varies with latitude and climate zone, from warm monomictic lakes at low latitudes, to dimictic lakes and cold monomictic lakes at relatively high latitudes, and to amictic lakes in polar regions (Lewis, 1983). The thermal structure of Lake Qiandaohu (29°22′–29°50′N, 118°36′–119°14′E) with a mean depth of 30 m and a lake area of 580 km^2 was discussed by Zhang et al. (2014). It typically exhibits a thermocline as stratification, the depth of which ranges from a few meters to tens of meters as the season changes. By contrast, the thermal stratification in Lake Taihu always has a shallow depth in the upper region. As a warm monomictic lake, Lake Qiandaohu requires a one-year cycle for the thermocline to change; it maintains thermal stratification in the spring, summer, and fall, and is mixed in the winter. In contrast, Lake Taihu is a warm polymictic lake that, except for rare examples of lasting stratification in the summer, stratifies in the daytime and mixes at night, on the cycle of one day. The thermocline in Lake Qiandaohu possesses a temperature gradient within only 1°C m^{-1}, whereas that in Lake Taihu usually exceeds 5°C m^{-1} (30 April). The water temperature in Lake Qiandaohu becomes less sensitive to depth as depth increases, and almost no vertical gradient occurs in the bottom layer. In other words, only the epilimnion layer in Lake Qiandaohu is a good indicator of climate forcing. In Lake Taihu, a shallower depth allows faster transport of heat from the surface. Although a vertical temperature gradient develops due to the change of heating rate with depth, the entire layer generally shows a consistent tendency of rapid variation, which resembles the epilimnion in deep lakes. Accordingly, compared to a deep lake whose thermal stratification changes depth, thickness, and strength with the seasons, the thermal stratification in Lake Taihu shows little seasonal differences but large variations in the short term.

Being the same as many other shallow lakes in temperate zone (Lewis, 1983), Lake Taihu is classified as a polymictic lake that retains the feature of diurnal mixing. For instance, the Lake Müggelsee, which has a mean depth of 4.9 m and an area of 7.3 km^2, located in the southeast of Berlin, Germany, is a shallow and polymictic lake with 79.3% of its stratification events shorter than 1 day (Wilhelm and Adrian, 2008). However, there are also some undeniable differences on thermal stratification between Lake Taihu and Lake Müggelsee. When Lake Taihu has its rare continuous thermal stratification (longer than one week) only in summer, Lake Müggelsee usually has its long-lasting stratification events more frequently (more than once per year in different seasons) and more durably (up to eight weeks). The greater depth, less fetch, and different local climate of Lake Müggelsee may account for its difference in thermal stratification from Lake Taihu (von Einem and Granéli, 2010).

3.2 *Representative response of thermal stratification to dominant factors*

Many factors affect the thermal stratification of a lake. For the shallow Lake Taihu, solar radiation and wind disturbance dominate the variations of thermal stratification (Fig. 4).

On clear days, strong thermal stratification is found in each season (e.g., 4 and 11 January; 22, 28, and 30 April; 13, 14, and 28 July; and 22 October). Among these cases, the maximum vertical temperature difference reached 8°C (30 April), and the minimum value was not lower than 2°C, making the water column stable. However, strong stratification did not always occur on clear days. In this situation, the vertical temperature difference was less than 2°C with weak thermal stratification (e.g., 19 January, 15 July, and 15–17 October) or a wholly mixed state (e.g., 21–23 January and 12 October). For instance, although solar radiation was strong on 22 January, a relatively high average wind speed of 5.83 m s^{-1} resulted in dynamic mixing that prevented a great vertical temperature difference from occurring.

With an extremely low temperature gradient, thermal stratification hardly ever appeared on overcast days that lacked solar radiation. Even if the lake was slightly stratified due to the residual impact of previous days, it rapidly mixed to a homogeneous state (e.g., 12 January and 3 July) due to dynamic mixing (wind disturbance) and thermal mixing (surface cooling).

Cloudy days are a transition between clear days and overcast days. On these days, strong thermal stratification was less developed (10 January), and the proportions of weak thermal stratification and mixed state were much higher than on clear days.

Having contrary effects on a water body, solar radiation (R_{sn}) and wind speed (W_s) are considered dominant factors that control the change of thermal stratification. In most cases (Fig. 4), the prevalent diurnal stratification results from strong solar radiation in daytime, making K_z (calculated from meteorological factors and water temperature), which represents the strength of turbulent mixing, to be nearly zero in spite of the considerable wind speed (e.g., 20–24 October). The coupled diurnal mixing happens after sunset when solar radiation has dropped. Simultaneously, K_z increases in nighttime, indicating prominent vertical convection. In addition, continuous period of high K_z exists when the wind is strong and the solar radiation gets weak (e.g., 4–12 July), in which cases turbulent mixing is dominant enough that K_z never drops to zero. To consider further, the monthly average R_{sn} and

W_s are calculated as seasonal thresholds. We regard the condition when the daily average R_{sn} is higher than the threshold while the daily average W_s is lower than the threshold as Type 1. Thus, the contrary condition is Type 2, when the daily average R_{sn} is lower than the threshold while the daily average W_s is higher than the threshold. All the cases that coincide with these two extreme types are averaged to obtain a representative pattern of the thermal structure in the four seasons (Fig. 5).

When R_{sn} is strong and W_s is weak (Figs. 5a–d; Type 1), solar radiation becomes a dominant factor that directly leads to a low MLD in daytime in the four seasons, among which spring and summer develop stronger thermal stratification than fall and winter. The thermal stratification in summer declines with difficulty at nighttime due to energy accumulation, whereas it is mixed thoroughly at night in other seasons, which is consistent with the analysis in Section 3.1. When R_{sn} is weak and W_s is strong (Figs. 5e–h; Type 2), wind speed becomes the dominant factor. The MLD reaches a high value in all four seasons, which means a wholly mixed state. A weak temperature inversion is found under Type 2 conditions near the surface due to heat loss from net radiation, sensible heat, and latent heat, which are influential when little energy is supplied by R_{sn}. In addition, there is a slightly warmer bottom region in spring, fall, and winter. This effect results from energy released by sediment as a heat source. In summer, the sediment receives energy as a heat sink from the water column due to intense energy accumulation; thus, no high-temperature zone is found.

By utilizing relative MLD (RMLD), the thermal structure in Lake Taihu can be divided into three different states: wholly mixed state, nearly mixed state, and stratified state (Fig. 6). As concluded, cases with thermal stratification mainly occupy the lower right region, which refers to Type 1. Most cases of wholly mixed state are distributed in the upper left region, which coincides with Type 2. It is worth noting that the cases of nearly mixed state show positive correlations between R_{sn} and W_s when R_{sn} is relatively high, which cannot be found due to few cases when both R_{sn} and W_s are lower. This result indicates that when R_{sn} increases, W_s must be higher to offset the stronger stratifying effect to maintain the thermal structure. As the nearly mixed state is a critical condition before the water column is wholly mixed, it can be inferred that when R_{sn} is higher, a higher W_s threshold is required to prevent the wholly mixed lake from stratifying. From Fig. 6, it can be seen that when R_{sn} is 100 and 200 W m^{-2}, the thresholds are approximately 2–3 and 4–5 m s^{-1}, respectively; when R_{sn} is higher than 300 W m^{-2}, the threshold can exceed 6 m s^{-1}.

3.3 *Wind-induced convection*

The concept of convection is usually used to describe the process whereby the gradient of the water property declines with prominent vertical mixing during the cooling period of the water body. However, in Lake Taihu, a specific quick convection during the short cycle of thermal stratification is found, which is also controlled by R_{sn} and W_s.

During the development and decline of thermal stratification, four types of daily patterns are summarized

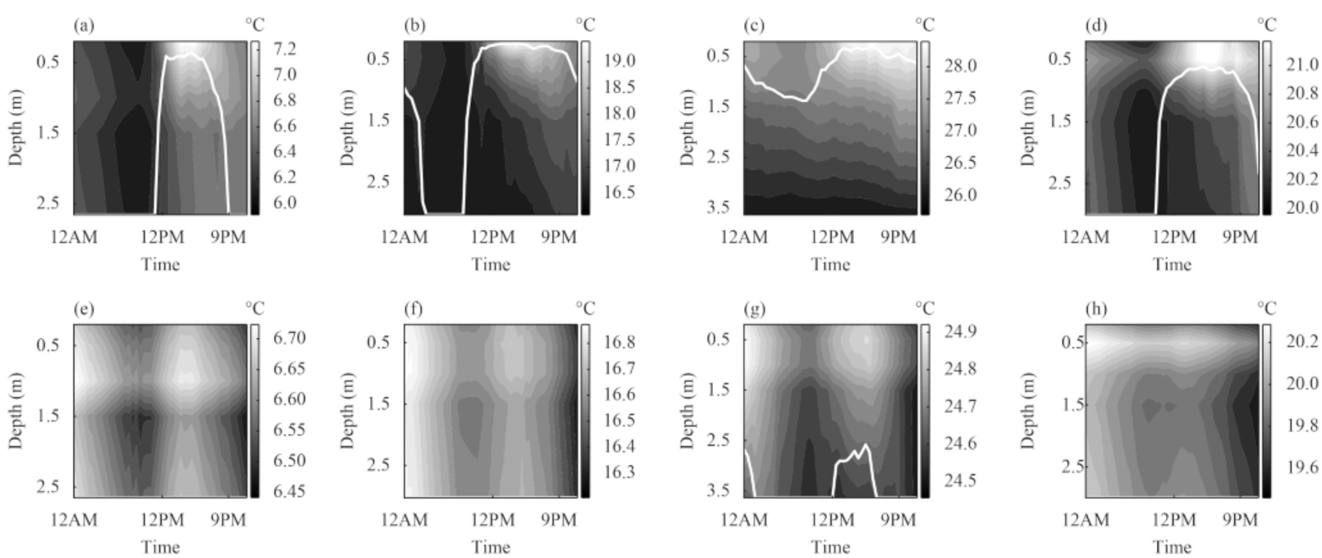

Fig. 5. The average response of water temperature and MLD to (a–d) Type 1 (high R_{sn} and low W_s) and (e–h) Type 2 (low R_{sn} and high W_s) conditions at the PTS site in (a, e) January, (b, f) April, (c, g) July, and (d, h) in 2015. The monthly average maximum depths are used in the four seasons, and the white line denotes the MLD.

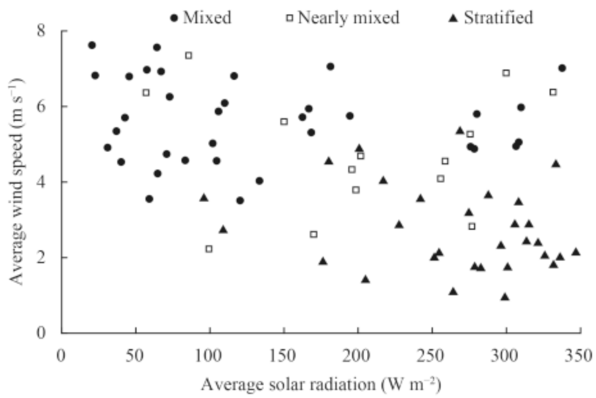

Fig. 6. Thermal stratification with different strengths and the corresponding R_{sn} and W_s. The circle points refer to the wholly mixed state with average RMLD of 100%. The squares refer to the nearly mixed state with average RMLD between 85% and 100%. The triangles refer to the stratified state with average RMLD lower than 85%. All data of RMLD, R_{sn}, and W_s here are chosen from daytime and are averaged to decrease the influence of extreme values. (RMLD is the relative MLD, which is the ratio of the MLD to the daily maximum depth).

(Fig. 7). When both R_{sn} and W_s are strong, thermal stratification develops and then slowly decreases (Fig. 7a). When W_s is dominantly high, a mixed state lasts for the entire day (Fig. 7b). However, when W_s suddenly increases, an existing stable thermal stratification is thoroughly mixed in a short time with the MLD increasing to maximum depth. This phenomenon, which occurs in both daytime (Fig. 7c) and nighttime (Fig. 7d), is here called wind-induced convection.

Furthermore, the frequencies of mixing, stratifying, and wind-induced convection, as well as its prerequisites, are shown in Table 1, and specific data of wind-induced convection are recorded in Table A1 in the Appendix. The presence of solar radiation in daytime makes the convection frequency far lower than in nighttime. For example, wind-induced convection appears in fall 17 times at night but only twice in daytime. Moreover, the lowest MLD before convection and the lowest W_s during convection at night are clearly lower than those in the day, indicating that high W_s is not necessary for night convection but stronger thermal stratification still can be turned even in this situation. By contrast, these prerequisites are stricter in daytime. For example, the lowest MLD before convection in spring daytime is 1 m deeper than that in nighttime, but the required W_s is nearly twice as high as that for night convection.

Regarding seasonal differences, Lake Taihu is wholly mixed most frequently in winter (17 days). Wind-induced convection occurs in the day for the most times (6 days), and the prerequisites for both the MLD and W_s are the lowest (0.85 m and 2.43 m s^{-1}, respectively). The MLD and W_s are also relatively low at nighttime (0.30 m and 2.41 m s^{-1}, respectively). This result means that winter is the most difficult season for thermal stratification to develop. Although the lake is stratified, it can be easily mixed by wind. In fall, there are only a few days of thorough mixing (7 days), while thermal stratification is commonly seen (20 days). However, wind-induced

Table 1. Number of wholly mixed days, stratified days, convection in daytime, and convection in nighttime. The lowest MLD before convection and the lowest W_s during convection are also shown. NoD denotes number of days

Season	Whole mixing	Stratification	Convection in daytime			Convection in nighttime		
			NoD	Value		NoD	Value	
Spring (31 days)	10	20	4	MLD	1.22 m	11	MLD	0.29 m
				W_s	4.04 m s^{-1}		W_s	2.04 m s^{-1}
Summer (28 days)	4	24	1	MLD	2.33 m	4	MLD	0.78 m
				W_s	4.46 m s^{-1}		W_s	3.91 m s^{-1}
Fall (27 days)	7	20	2	MLD	1.23 m	17	MLD	0.42 m
				W_s	2.77 m s^{-1}		W_s	1.91 m s^{-1}
Winter (31 days)	17	14	6	MLD	0.85 m	7	MLD	0.30 m
				W_s	2.43 m s^{-1}		W_s	2.41 m s^{-1}

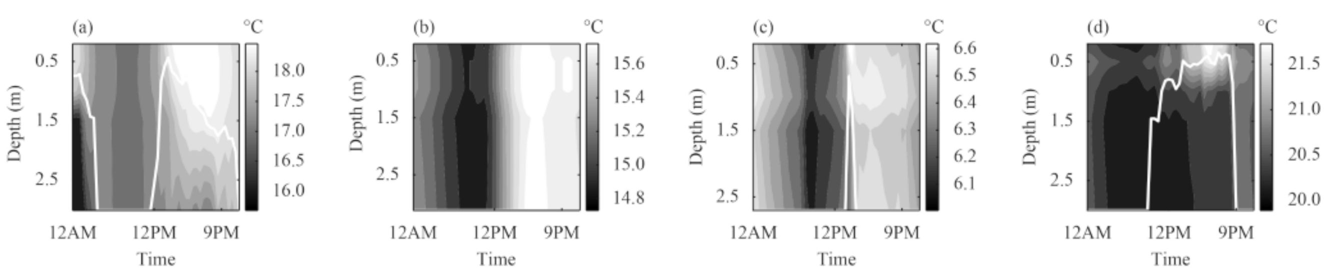

Fig. 7. Four typical cases for changes in water temperature and the MLD: (a) thermal stratification slowly decreases on 23 April; (b) no thermal stratification appears on 17 April; (c) developed thermal stratification suddenly disappears in daytime on 18 January; and (d) developed thermal stratification suddenly disappears in nighttime on 18 October. The white line denotes the MLD.

convection at night occurs the most often in fall (17 days) with the lowest requirement for W_s (1.91 m s^{-1}). Therefore, the daily cycle of the thermal structure is more obvious in fall because the easily stratified water is usually mixed at night. For summer, the lake is wholly mixed on only 4 days. Wind-induced convection is the hardest to induce, as shown by the fewest times of convection whether in day (1 day) or night (4 days). Moreover, its prerequisite values of the MLD and W_s are the highest (2.33 m and 4.46 m s^{-1}, respectively, in daytime and 0.78 m and 3.91 m s^{-1}, respectively, in nighttime). These values in spring are all at intermediate levels. Finally, wind-induced convection prevails in winter and fall but becomes rare in summer when thermal stratification is easy to maintain.

4. Conclusions

In this study, the data from the PTS site in the Lake Taihu Eddy Flux Network in 2015 are used to analyze the variation in thermal stratification and vertical mixing in Lake Taihu. Stable thermal stratification is stronger in spring and summer than in winter but becomes weaker in fall. Compared to a deep lake at similar latitude, Lake Taihu stratifies at a comparatively shallow depth that is always in the upper region. Its vertical temperature gradient is greater (usually exceeds 5°C m^{-1}), and the variation tendency of the entire layer is more uniform. Thermal stratification in Lake Taihu does not change obviously with seasons but varies greatly in the short term (one day to a few days). Therefore, Lake Taihu should be classified as a warm polymictic lake. Many shallow ploymictic lakes share the same characteristic of diurnal mixing. However, differences on thermal stratification among them are also prominent. The duration and frequency of long-lasting (more than one week) thermal stratification vary with location and morphology, which in detail, may be caused by different local climate, lake depth, and fetch.

Based on comparison between different MLD criteria, the traditional difference criterion with ΔT = 0.2°C is shown to be a more suitable method for determining the MLD in Lake Taihu, especially when a weak temperature inversion exists at the surface. In this situation, the MLD from Kara's optimal definition usually differs from the logical value by nearly 2 m.

Weather conditions are influential. Strong thermal stratification occurs more frequently on clear days than on cloudy days. When it is overcast, the lake is almost mixed. Indeed, different weather conditions control the thermal structure of the lake mainly through solar radiation (R_{sn}) and wind speed (W_s), which are the two dominant factors with totally contrary effects on thermal stratification. The most direct results are the diurnal stratification and convection, as well as the distinct patterns under the combination of these two factors. When high R_{sn} corresponds to low W_s, strong thermal stratification appears in each season, among which the lake is more stratified in spring and summer than in fall and winter. When R_{sn} is low but W_s is high, the lake is well mixed in each season with a weak temperature inversion near the surface. In this case, a warmer region at the bottom is also found in spring, fall, and winter when sediment becomes a heat source. This effect cannot be seen in summer due to heat accumulated in the water column. Solar radiation and wind speed are positively correlated for the nearly mixed state. When R_{sn} increases, a higher W_s threshold is required to maintain the mixed state. R_{sn} values of 100 and 200 W m^{-2} need thresholds of approximately 2–3 and 4–5 m s^{-1}, respectively. When R_{sn} is higher than 300 W m^{-2}, the threshold can exceed 6 m s^{-1}.

In this study, the PTS site is chosen because of its good water quality, few macrophytes, and more spacious fetch. Furthermore, the effects of meteorological conditions are mainly discussed. Future work should involve other zones in Lake Taihu to take into consideration the factors such as plankton, macrophytes, and morphology. Thus, more comprehensive research can be performed. Moreover, it is undoubted that the W_s threshold increases with R_{sn}. However, only approximate values have been obtained to date because there are few cases for analysis. A specific and quantitative law must be found between these factors.

Prominent convection occurs in Lake Taihu due to wind disturbance. This effect occurs more easily at night than in daytime. As the season with the least thermal stratification, winter has the greatest tendency of convection in daytime. In fall, thermal stratification and wind-induced convection are both common, showing a typical daily cycle of thermal structure. A stratified state is easy to maintain in summer, and the prerequisites for MLD and W_s are the strictest; thus, the least number of convection occurs in summer. Generally, convection results in a substantial change in the thermal structure in a lake. In deep lakes, convection chiefly results from seasonal variations of thermal properties in the water (Socolofsky and Jirka, 2005), controlling the growth of algae and having a great impact on substance distribution in the lake (Gonçalves et al., 2016). However, the diurnal convection in shallow Lake Taihu is caused more by wind disturbance, which may help in studies of algal blooms and the uncertainty of flux in Lake Taihu, similar to other polymictic lakes (Wilhelm and Adrian, 2008). We use only the MLD to depict convection in one dimension. To deeply study the mechanism underlying convection, the flow field and what affects it in three-dimensional space must be considered. Therefore, subsequent observational and modeling studies are needed.

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Appendix

Table A1. This table records average R_{sn}, W_s, MLD, and RMLD in daytime as well as the thermal stratification in each day in 2015. If a thermal stratification declines in the next day prior to the sunrise, it is considered a mixing process for the previous day (days of wholly mixed state are not included). The last two columns of the table show the MLD before and the W_s during wind-induced convection

Date (mth.day)	R_{sn} (W m^{-2})	W_s (m s^{-1})	MLD (m)	RMLD (%)	Start time	End time	MLD before convection	W_s during convection
1.2	321.32	1.79	1.31	48.27	12:00	19:30	\	\
1.3	258.65	3.58	2.48	91.62	13:00	15:00	1.41	4.08
1.4	278.60	1.08	0.46	17.11	11:00	22:00	1.75	2.85
1.8	296.29	1.71	1.45	54.59	13:00	17:30	0.30	2.53
1.9	276.74	2.29	2.20	82.62	13:00	15:30	1.08	2.45
1.10	282.73	1.58	0.41	15.47	10:30	23:00	1.19	2.41
1.11	298.96	1.08	0.28	10.48	10:30	20:30	0.60	5.48
1.17	305.68	1.82	1.22	46.08	12:00	17:30	0.46	5.15
1.18	201.73	4.59	2.43	90.11	13:00	14:30	1.24	4.85
1.19	336.16	1.82	0.82	31.02	11:00	00:00	1.41	5.46
1.21	275.52	6.66	2.41	90.86	10:00	12:00	0.85	8.29
1.24	242.01	3.86	1.86	69.90	11:00	15:30	0.91	5.69
1.26	99.32	2.51	2.51	95.33	15:00	16:00	1.16	2.43
1.31	274.64	2.23	1.88	71.88	13:00	18:00	1.48	4.93
4.1	268.66	5.99	1.78	60.92	\	16:00	1.62	7.35
4.2	299.79	7.56	2.45	82.51	12:00	15:30	1.22	6.47
4.4	150.02	4.88	2.77	93.75	13:00	14:30	1.86	4.04
4.8	481.92	1.63	1.16	37.32	10:30	00:30	0.59	6.51
4.9	308.20	2.73	1.11	34.71	10:30	18:30	1.29	4.60
4.10	420.51	0.90	0.79	24.70	09:30	23:30	0.29	6.23
4.11	469.97	2.97	0.60	18.85	08:30	23:30	1.69	4.43
4.12	473.40	3.11	1.02	32.01	10:30	19:00	0.31	12.33
4.16	354.88	5.81	2.12	69.00	10:00	15:00	\	\
4.18	313.53	2.34	0.89	29.05	11:00	\	\	\
4.19	264.08	1.16	0.73	24.09	\	21:00	1.23	9.45
4.21	485.16	1.24	0.36	11.74	08:30	\	\	\
4.22	528.78	1.99	0.38	12.39	08:30	03:30	1.46	3.95
4.23	507.46	4.31	1.49	49.45	11:00	23:30	2.20	3.61
4.24	204.94	0.97	0.49	16.49	09:00	\	\	\
4.25	499.04	1.31	0.29	9.81	\	01:00	1.64	2.04
4.26	539.08	3.97	0.73	24.58	09:00	19:30	\	\
4.27	460.94	5.01	2.76	93.40	13:30	16:00	2.29	4.64
4.28	481.11	2.45	0.31	10.54	07:30	21:30	1.35	14.19
4.30	530.95	1.41	0.25	8.58	07:30	22:00	1.16	6.50
7.1	386.39	2.63	1.21	33.88	10:00	24:00	\	\
7.2	325.88	1.87	0.96	26.78	08:30	03:00	\	\
7.3	254.57	2.01	0.74	20.71	08:00	01:30	\	\
7.7	195.77	3.88	3.34	93.55	11:00	13:00	2.33	4.46
7.8	198.46	3.50	2.92	81.48	11:00	18:30	2.79	3.92
7.9	216.91	4.24	2.26	62.19	10:30	21:00	2.34	6.89
7.10	448.43	6.73	1.75	48.60	09:00	20:00	\	\
7.12	300.11	7.20	3.27	87.85	15:00	20:30	\	\
7.13	450.30	1.99	0.39	10.38	08:00	\	\	\
7.14	394.41	1.85	0.41	10.89	\	\	\	\
7.15	424.26	4.32	1.38	36.59	\	\	\	\
7.16	200.72	4.66	2.14	57.34	\	21:00	\	\
7.17	85.65	6.63	3.59	97.39	11:00	16:00	\	\
7.18	95.96	3.07	2.53	68.37	10:30	01:00	2.64	5.34
7.19	180.15	4.45	1.82	49.47	09:00	19:00	0.78	7.70
7.20	446.49	1.47	1.17	31.48	07:00	\	\	\
7.21	251.33	1.67	0.95	25.65	\	\	\	\
7.22	421.27	2.55	0.55	15.01	\	\	\	\
7.23	108.95	2.40	1.56	42.38	\	\	\	\

to be continued

Continued from Table A1

Date (mth.day)	R_{sn} (W m^{-2})	W_s (m s^{-1})	MLD (m)	RMLD (%)	Start time	End time	MLD before convection	W_s during convection
7.24	227.59	2.78	0.92	24.91	\	\	\	\
7.25	300.80	2.04	1.06	29.12	\	\	\	\
7.26	403.39	1.88	0.92	25.27	\	\	\	\
7.27	424.68	2.65	0.63	17.27	\	\	\	\
7.28	532.48	3.21	0.47	13.19	\	\	\	\
10.8	56.91	6.39	2.84	92.66	12:30	14:00	1.50	7.94
10.10	331.48	6.70	2.77	90.04	15:30	17:30	1.50	7.00
10.11	411.54	1.99	1.16	37.63	10:00	20:00	1.40	3.24
10.12	394.13	3.11	1.33	43.44	10:00	18:30	1.89	3.00
10.13	375.72	1.45	0.93	30.49	10:00	05:00	1.38	1.91
10.14	176.24	1.82	1.80	59.02	12:30	21:00	1.69	3.78
10.15	370.59	1.99	0.65	21.50	09:00	01:00	0.42	4.62
10.16	331.76	1.20	1.21	39.81	09:30	01:00	1.48	2.61
10.17	407.25	1.82	0.64	21.25	09:00	23:30	1.08	5.13
10.18	387.09	1.87	0.71	23.60	08:30	21:00	0.86	4.86
10.19	371.39	3.20	1.25	41.78	10:30	22:00	2.28	5.97
10.20	346.84	1.67	0.91	30.55	10:00	01:00	\	\
10.21	377.13	1.70	0.85	28.55	09:00	21:30	1.19	4.82
10.22	354.33	1.61	0.63	21.15	09:30	21:30	1.41	4.83
10.23	380.10	2.16	0.81	27.37	09:30	01:00	1.45	6.06
10.24	315.15	2.59	0.95	32.53	10:30	20:00	1.80	6.40
10.25	287.78	3.17	1.69	58.08	11:30	19:30	2.10	7.50
10.26	333.36	3.54	1.71	58.27	21:30	22:00	1.54	9.90
10.28	169.96	2.41	2.56	88.09	10:00	12:00	1.23	2.77
10.31	255.60	2.96	2.45	85.18	15:00	17:30	1.31	2.53

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