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Spatial and temporal variations in water temperature in a high-altitude deep dimictic mountain lake (Nam Co), central Tibetan Plateau

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ABSTRACT

Water temperature and the related thermal structure and stratification of a lake are very important to lake ecosystems because of their significant effects on the vertical exchanges of dissolved and particulate matter. In this study, we present high resolution, seasonal variations in water temperature at different depths of a large deep lake on the central Tibetan Plateau. The results show that Nam Co is a typical dimictic lake whose thermal stratification begins and ends in early June and early November, respectively. Increases in the water temperature during spring and the establishment of thermal stratification in the eastern small sub-basin occur approximately one month prior to the main basin which is likely caused by the different morphometry, different water transparency during spring, and the possible presence of a spring thermal bar. The Schmidt stability of the water column is directly controlled by surface water temperature. During the ice-covered period, the homogeneous water temperature exhibits a continuous increasing trend from approximately 0.5 °C to 3.5 °C. The daily mean surface water temperature of the main open lake area is highly correlated to the air temperature but shows a hysteresis effect of approximately 38 days, which shows the significant heat storage in such a large deep lake. Nam Co is a typical lake in this area in terms of its altitude, water depth and climatic conditions, so our results have broader significance for limnological and paleolimnological studies of similar lakes on the Tibetan Plateau.

Introduction

The water temperature distribution of a lake, which is directly controlled by solar radiation, is one of its most basic and important intrinsic characteristics. The upper 2 m of lake water absorb over one-half of the Sun's incoming radiation, and the amount of light energy decreases exponentially with increasing water depth (Wetzel, 2001). Thus, a typical vertical profile of water temperature in lakes of moderate depth shows thermal stratification that is characterized by three strata: the epilimnion, metalimnion (thermocline) and hypolimnion (Hutchinson, 1957). Lakes show various thermal stratification patterns in different climatic regions, which are mainly controlled by the latitude and altitude. A classification has generally been established and is widely accepted based on the thermal features of lakes, in which six lake types were specified with different stratification and circulation patterns: amictic, cold monomictic, dimictic, warm monomicitic, oligomictic and polymictic (Hutchinson, 1957; Wetzel, 2001).

The Tibetan Plateau (TP), which is a unique geographic unit on the globe with a mean elevation of >4000 m a.s.l., was recently called a third pole region according to the air temperature and ice volume (Qiu, 2008). A large number of modern lakes are distributed across the TP, forming one of the largest lake zones in the world. The ecological importance of the lakes on the TP has been increasingly recognized and has triggered increasing interest in limnological and paleolimnological studies. Water temperature measurements have been reported for some lakes, which showed that thermal stratification occurs in all these high-altitude lakes (e.g., Guan et al., 1984; Li et al., 2001; Murakami et al., 2007; Wang et al., 2009, 2013; Zhu et al., 2010a). However, most of the reported water temperature profiles were based on single measurements, which provided no insight into the circulation patterns of these lakes. Limnological stations are lacking across the entire TP, and only a few lakes have been monitored for at least one season. Wang et al. (2014) illustrated Bangong Co and Dagze Co as dimictic and meromictic lakes, respectively, based on one-year temperature measurements. Water temperature was observed from Ngoring Lake, a

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dimictic lake in the Yellow river source area of TP and thermal regime, air-lake interaction and surface energy budget were studied by using monitoring data and models (Li et al., 2015; Wen et al., 2016; Kirillin et al., 2017).

Nam Co is a large and deep lake at a high altitude in the central TP. Modern limnological and hydrological features (e.g., Wang et al., 2009, 2010; Zhou et al., 2013; Gou et al., 2017) and the sedimentation patterns of surface sediment (e.g., Wang et al., 2015) as well as paleoenvironmental changes (e.g., Zhu et al., 2015; Kasper et al., 2015) have been reported. However, some aspects remain unclear due to the lack of consecutive observations, such as how the water quality of the lake water varies during different seasons and how thermal stratification develops within a year.

Few attempts have been conducted to estimate the annual evaporation from Nam Co's surface, and the results have been quite different, including 635 mm (Ma et al., 2016), 658 mm (Haginoya et al., 2009) and 832 ± 69 mm (Lazhu et al., 2016). Among these works, the simulated evaporation by the Flake model was validated against the observed lake temperature profile (Lazhu et al., 2016). Therefore, monitoring the water temperature at different water depths can provide important information to evaluate heat exchange between lake water and the overlying air and to calculate the heat budget of a lake.

In this study, we present the water temperature variability based on high-resolution in situ continuous monitoring at two stations in Nam Co, with a focus on the seasonal variations in thermal stratification to specify the circulation type of this lake. Moreover, different temporal behaviors of thermal stratification development at two monitoring stations are compared. Finally, the relationships between the lake surface temperature and air temperature are discussed.

Study area and methods

Study area

Nam Co is located in the central part of the Tibetan Plateau (90°16′ to 91°03′E, 30°30′ to 30°55′N, Fig. 1) at an altitude of approximately 4730 m a.s.l. >60 tributaries flow into the lake during the summer season, most of which are distributed along the western and southern shores of the lake. The largest rivers originate from the Nyainqentanglha Range to the southwest, whereas almost no rivers originate from the north (Fig. 1).

A bathymetric survey showed a large deep-water area in the central portion of the lake and the deepest recorded point is 98.9 m. A small sub-basin with a maximum depth of ~60 m could be observed in the eastern area (Fig. 1C, Wang et al., 2009). According to the calculated area from satellite images and measured water depth data, the water volume has been estimated to be 783.23 × 10^8 m^3 and 863.77 × 10^8 m^3 for the years 1971 and 2004, respectively. Over the same period, the lake area increased from 1920 km^2 to 2015 km^2 (Zhu et al., 2010b).

Climatically, Nam Co is located in the monsoon-influenced transition zone between semi-humid and semi-arid areas with an annual mean air temperature and precipitation of approximately 0 °C and ~450 mm, respectively. The precipitation during the warm season (May–September)

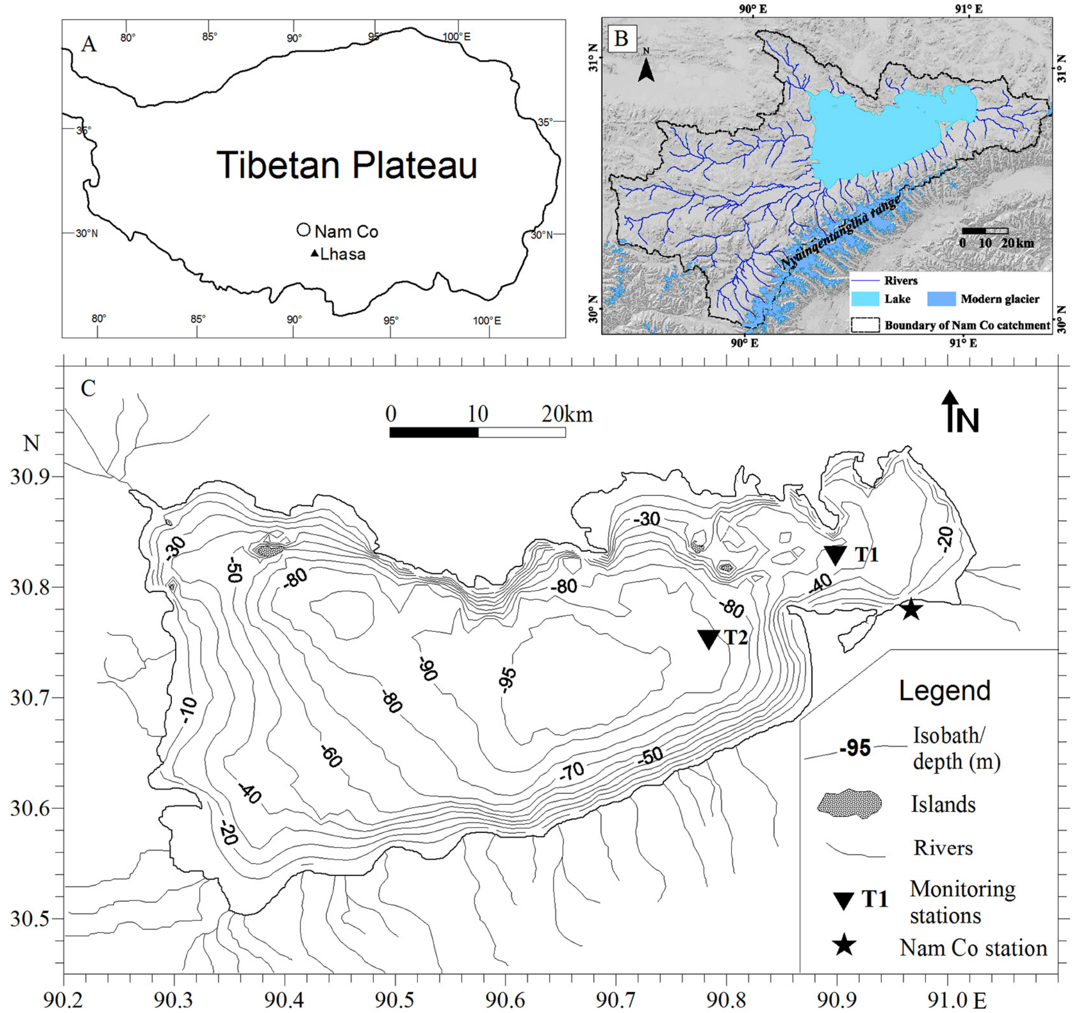

Fig. 1. Map that shows the location of Nam Co on the Tibetan Plateau (A), rivers and glaciers in the Nam Co catchment (B) and the positions of stations T1 and T2 in Nam Co (C).

constitutes 91% of the total annual precipitation (Guan et al., 1984). The mean annual wind speed is 4 m s^{-1}. The maximum monthly mean wind speed (6.1 m s^{-1}) occurs in January. The dominant wind directions are southeast to west throughout the year (You et al., 2007).

Methods

This monitoring of water temperature in Nam Co was conducted with a multi-probe water quality sonde (Hydrolab DS5, Hach, USA), water temperature data loggers (VEMCO Minilog-II-T, Canada; accuracy: ±0.1 °C from −5 °C to 35 °C; resolution: 0.01 °C) and online multi-parameter probes (CTD 90 M) from Sea & Sun Technology (SST, Germany). Regular water quality profiling was conducted (Hach Hydrolab DS5) at two stations in two sub-basins of the lake: one in the eastern area (station T1, ~57-m depth) and the other in the main western basin (T2, ~93-m depth) (Fig. 1C). The field investigation campaigns (frequency: two to four weeks) were conducted from early April to late November from 2011 to 2014, covering almost the entire open lake period and a portion of the ice cover season. Temperature data loggers were deployed throughout the entire study period at station T2 from late October 2011 to early July 2014 at depths of approximately 6 m, 16 m, 21 m, 26 m, 31 m, 36 m, 56 m and 66 m (a logger at 46 m depth was lost, and the loggers at 21 m and 31 m depths were established in May 2013). The logging interval was 10 min. Two SST probes were deployed at the surface (~3-m depth, late May 2012 to middle September 2013) and the bottom (~83-m depth, late May 2012 to early July 2014) of the mooring at station T2 with a recording interval of 2 h.

Meteorological data were recorded at the Nam Co Monitoring and Research Station for Multisphere Interactions (Nam Co station) by an automatic weather station system (a Vaisala MIRO520), which is located at the southeastern part of Nam Co (Fig. 1C).

Results and discussion

The circulation type of Nam Co determined by the observed water temperature data

Complete freezing and break-up in Nam Co occur in early February and mid-May, respectively, with an average ice cover period of ~90 days (Qu et al., 2012). After the lake ice completely melts, the water temperature shows isothermy at both stations. Along with heating from the surface, the water temperature of the upper layer continuously increases until thermal stratification forms. During autumn, the epilimnion increasingly deepens until the entire water body returns to a homogeneous thermal status, finally entering a winter stagnation period (Fig. 2). Thus, Nam Co experiences vernal turnover, estival stable stratification, autumnal circulation and hibernal ice cover. Two full circulations occur in one year in Nam Co which is characteristic of a typical dimictic and holomictic lake in a temperate zone.

In general, lake types that are based on thermal and circulation characteristics depend on altitudinal and latitudinal distributions. Wetzel (2001) proposed a schematic arrangement of thermal lake types based on a modification from Hutchinson and Löffler (1956), in which dimictic lakes occur within a limited area (an anamorphic triangle), mainly at an altitude of <4000 m and latitude of 40°–60°. Nam Co, which is located at an altitude of >4700 m and a relatively low latitude of 30°, is obviously far beyond the range of dimictic lakes (Fig. 3A). Wetzel (2001) noted that elevation is relatively unimportant to lake classification, except for the highest elevations. Lewis Jr. (1983) proposed a revised classification of lakes with some modification from Hutchinson and Löffler (1956) and included water depth information and adjusted latitudes from elevation, in which eight lake types were specified. Nam Co is located within the range of dimictic lakes in this diagram (Fig. 3B), which reflects that the elevation, latitude and water depth are all important when determining lake types in terms of thermal stratification.

Salt contributes to water density and thus can affect the stratification of lakes. The salinity of lake water is the second most important factor after temperature that affects vertical and horizontal mixing. The temperature at maximum density (T_{md}) decreases with increasing salinity (Boehrer and Schultze, 2008). Although Nam Co is a brackish lake, the salinity is rather low, and vertical fluctuations in the conductivities that were observed during the stratified periods in the main basin showed almost constant values vertically (Wang et al., 2009); therefore, the effect of salinity on stratification can be assumed to be negligible in Nam Co.

Seasonal variations in the water temperature and characteristics of thermal stratification in the main basin (station T2)

At station T2, the water temperature at different depths showed distinct seasonality (Figs. 4 and 5). During early June, the surface temperature (represented by temperatures at 3-m and 6-m depth, which show almost identical curves) rose rapidly until mid-August from 3.5 °C to 12.0 °C. From mid-August onwards, the surface temperature continuously decreased to ~5 °C in mid-November, when the entire water body was mixed. This mixed water body showed very small temperature differences from the top to the bottom (Figs. 4 and 5), which lasted until June of the following year. The coldest period occurred in mid-January with a temperature of 0.5 °C. During the ice-covered period, the temperature at all depths slowly increased from 0.5 °C to 3.5 °C (Fig. 4). After this stable stratification was established, the temperature of the deep water was homogeneous and rather stable, with an observed minimum temperature of ~3.4 °C (even lower in late June and early July of 2013) from mid-June to late October (Fig. 4). This temperature could be assumed as the T_{md} of Nam Co's lake water, which is a function of the pressure and salinity. The T_{md} can be empirically calculated by using the local air pressure and salinity (Chen and Millero, 1986). The T_{md} of Nam Co is estimated to be 3.60 °C after the pressure and salinity are set to 0.57 bars and 1.7 g l^{-1}, respectively (Wang et al., 2009). The minor offset (~0.2 °C) between the observed and theoretical T_{md} could be attributed to the error of the temperature logger and the different salt composition of Nam Co than assumed by Chen and Millero (1986).

We used data from June 2013 to July 2014, which covered an entire hydrological year at different depths to show some characteristics of the vertical temperature variability (Table 1). The minimum temperatures that all appeared in January generally increased with increasing depth reflecting the reverse thermal stratification, whereas the average and highest observed temperatures at different depths (appeared during the thermal stratification period in summer) declined with increasing depth (Table 1). The maximum temperature of water column above 31 m depth were observed during the typical thermal stratification period whereas that of below 31 m depth appeared just before the onset of summer thermal stratification; water temperature in deep part quickly increased until the entire water body become homogeneous (Fig. 4).

High-resolution recordings (10 min) of water temperature can present short-term fluctuations in greater detail (Fig. 6). Abrupt short-term temperature fluctuations were recorded at different depths during the entire study period, some of which could be simultaneously detected in several layers (Fig. 6). Among these abrupt fluctuations, the highest temperature occurred at 36-m depth on September 25, 2012, which reflects an abrupt temperature fluctuation of >3 °C in amplitude within four hours (3:00–7:00) and was only detected at this depth (Fig. 7). These abrupt fluctuations in water temperature at a certain depth indicate internal wave activities. These internal waves can cause abrupt temperature fluctuations of up to 6 °C at a certain depth, as illustrated in Fig. 6 (at 26 m water depth in mid-September 2012).

Rapid changes in water temperature were simultaneously recorded at all depths within the thermocline layer, but the amplitude of these

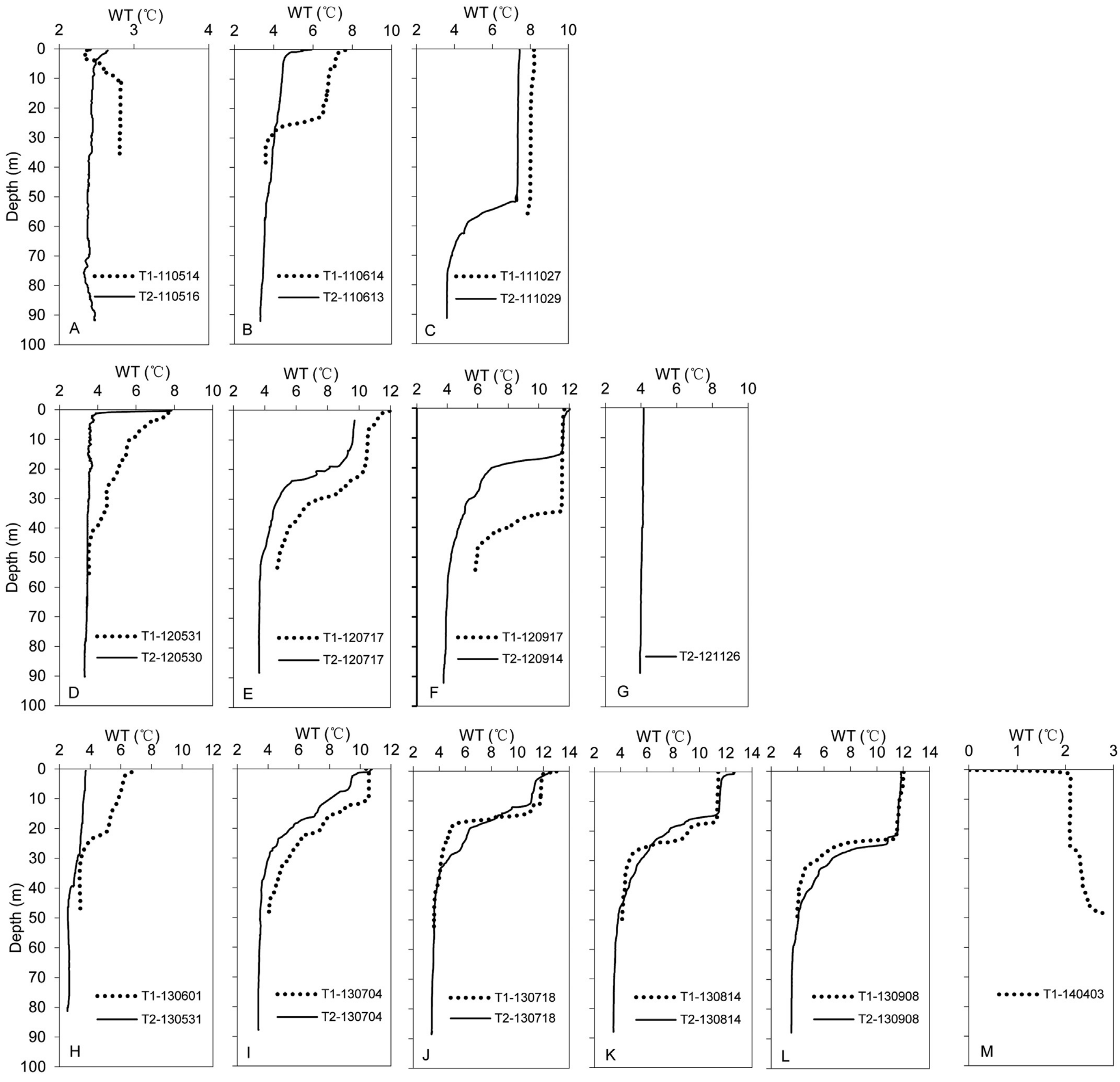

Fig. 2. Comparison of in situ water temperature profiles from different seasons during the study period at stations T1 and T2 (date format: yy/mm/dd).

changes decreased with increasing depth, which indicates that these internal wave activities were more intensive in the upper portion of the thermocline. When the surface cooled during autumn, the mixed layer deepened towards the bottom of the lake, which caused abrupt temperature changes with an amplitude of >1 °C (maximum 2 °C) at 56-m to 83-m depth in late October of both years, when the thermal stratification approached its end (Fig. 4). The fast increase in temperature in the deep area that was observed during autumn is typical in dimictic lakes and could be attributed to the metalimnion crossing this depth (see Fig. 2C).

The onset of thermal stratification is one of the most important processes within a lake, which affects the other parameters of the water quality and thus the lake ecology (Boehrer and Schultze, 2008; Woolway et al., 2014). The criteria for determining thermal stratification in lakes always vary according to the different purposes of studies (Foley et al., 2012; Engelhardt and Kirillin, 2014). A temperature difference of >1 °C between surface and deep water is a widely used indicator to define the process of thermal stratification in lakes (Stefan et al., 1996; Foley et al., 2012; Woolway et al., 2014; Butcher et al., 2015). Recently, a number of studies showed that the characteristics of thermal stratification in lakes sensitively respond to long-term regional climate change, which highlights the significance of investigations of thermal stratification in lakes (e.g., Foley et al., 2012; Marshall et al., 2013; Vincon-Leite et al., 2014; Zhang et al., 2014; Butcher et al., 2015; Trumpickas et al., 2015).

We used the temperature difference between 6-m and 66-m depth for a comparison with station T2 at Nam Co because these depths both had continuous records during the entire study period with the same type of data logger (Fig. 8). The onset of thermal stratification in Nam Co occurred in late May/early June, whereas the end of thermal stratification occurred in early to mid-November. Thus, the duration of thermal stratification was 153 and 157 days in 2012 and 2013, respectively (Table 2).

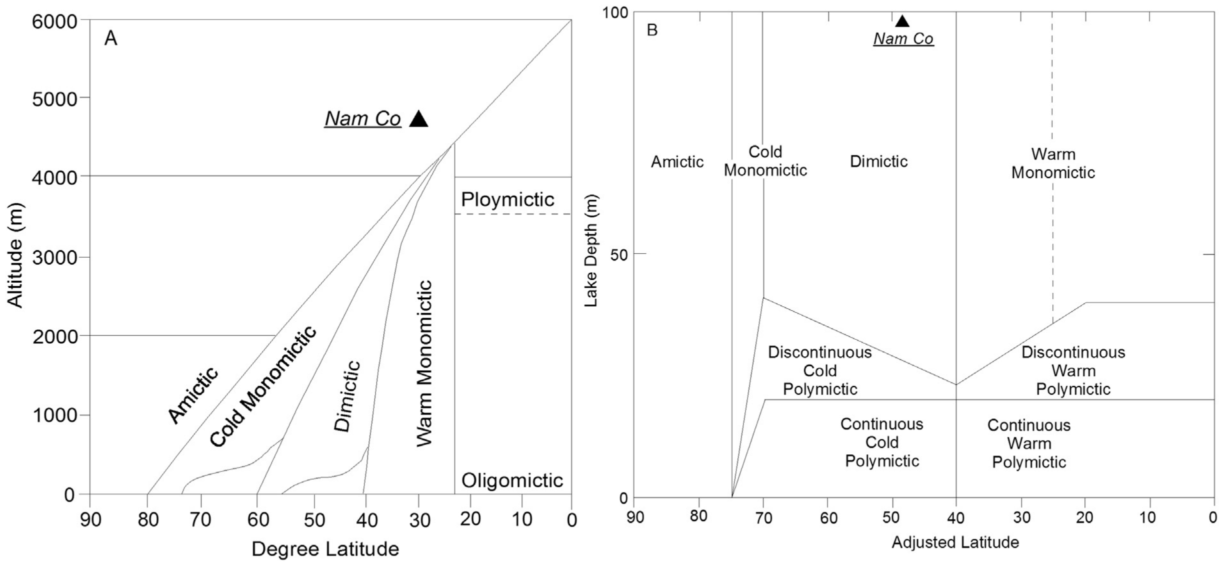

Fig. 3. Lake Nam Co in the schematic diagrams of thermal classification of Hutchinson and Löffler (1956) (A) (modified from Wetzel, 2001) and Lewis Jr. (1983) (B) (modified from Lewis Jr., 1983).

Distinct periods of inverse stratification occurred during winter stagnation (Fig. 8) when Nam Co was covered by lake ice. The temperature at the bottom layer was >1 °C higher than that of the surface water during most of the inverse stratification periods, which was also observed at station T1 in April 2014 (Fig. 2M).

The Schmidt stability is a useful measure to indicate the strength of stratification and is described as the energy (J m^{-2}) that is required to mix the water column; higher Schmidt stability indicates stronger stratification (Idso, 1973; Wetzel, 2001).

The Schmidt stability of Nam Co in 2013 was calculated by the Lake Analyzer model (Read et al., 2011) based on the definition as

$$S_T = \frac{g}{A_S}\int_0^{Z_D}(Z-Z_v)\rho_z A_z \partial z$$

where S_T is Schmidt stability, g is the acceleration due to gravity, A_S is the surface area of the lake, A_Z is the area of the lake at depth Z, Z_D is the maximum depth of the lake, Z_v is the depth to the center of volume of the lake, and ρ_z is water density at depth Z, assuming negligible effects of any solutes on density, ρ_z can be calculated from a give temperature T_z (in °C) as proposed in Martin and McCutcheon (1999):

$$\rho_z = \left[1-\frac{T_z+288.9414}{508929.2\cdot(T_z+68.12963)}(T_z-3.9863)^2\right]\cdot 1000$$

The results of calculation exhibited similar seasonal patterns as the surface water temperature (Fig. 9A), which showed a rapid increase that began in mid-June, reached a maximum value in mid-September, and then decreased swiftly afterwards to a stable level in mid-November (Fig. 9A). The stability of a lake is strongly influenced by its size and morphometry resulting in a large range of calculated Schmidt stability (Wetzel, 2001). In a study across 39 West African lakes, Kling (1988) reported the Schmidt stability ranged from 0 to 5784 J m^{-2}. The seasonal variation of stability in Nam Co during the entire 2013

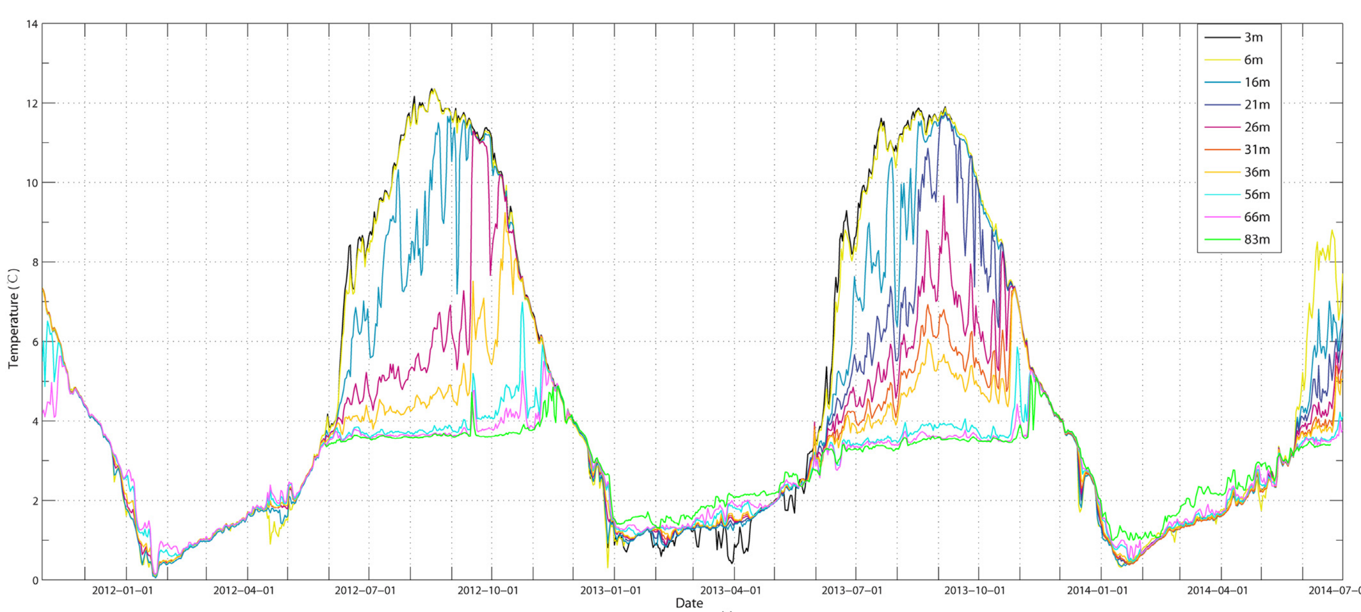

Fig. 4. Daily mean water temperature variation at different depths at station T2 in Nam Co from November 2011 to July 2014.

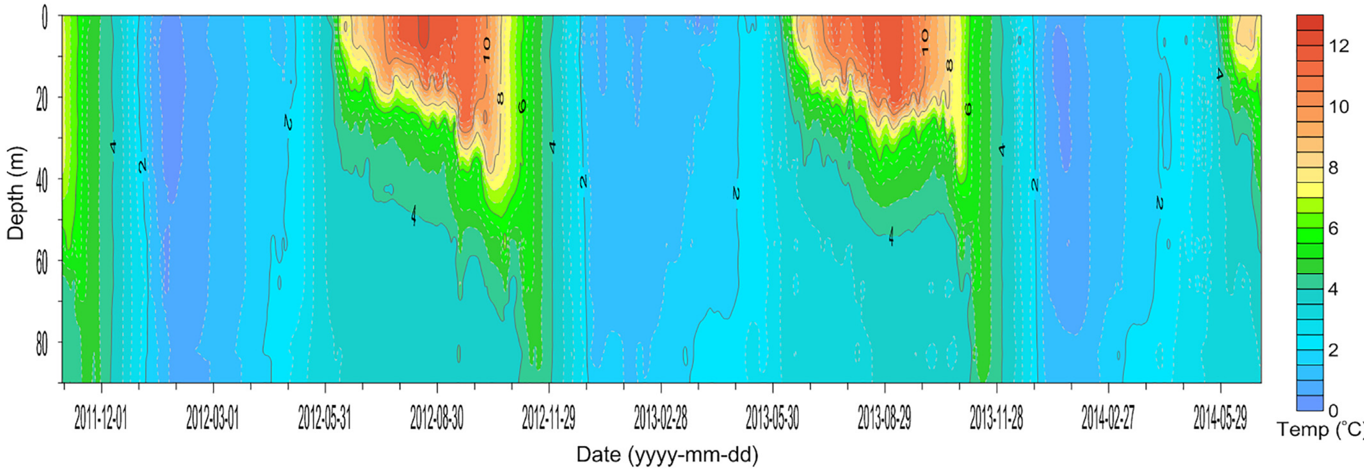

Fig. 5. Time-depth contour plot of the daily mean water temperature variation in Nam Co from November 2011 to July 2014.

showed a large range from −53 to 2287 J m^{-2} which was much higher than Bangong Co and Dagze Co in strong stratification period (Wang et al., 2014) likely caused by the much deeper water depth of Nam Co.

There were generally similar patterns between surface water temperature and stability (Fig. 9A) which probably indicated some correlation between them. During the ice covered period, the surface water temperature slowly increased and the stability showed a continuous declining trend with very low absolute values indicating the water body was prone to a uniform regime. The minimum value of stability appeared on June 4th and surface water temperature was 3.77 °C which was very close to the T_{md} of Nam Co. On June 4th of 2013, the thermal stratification was established (Table 2) indicating the spring overturn was finished. After that, the stability enhanced rapidly with increasing surface water temperature making the entire water body very stable.

The stability was influenced by surface water temperature, and these two variables showed a strong binomial relation in general based on the entire year of 2013 (Fig. 9B). More specifically, increasing surface water temperature makes the water body becomes unstable during the ice-covered period until the spring overturn occurred. However, after the thermal stratification established, increasing temperature can greatly enhance the stratification and thus stabilize stratification.

Thermodynamics and mixing regime during ice-covered periods

Ice-covered periods are very important to ecosystem and sedimentation processes in a dimictic lake, especially when these periods are rather long. Ice-covered periods in lakes remain poorly investigated, and winter processes are not understood as well as summer periods (Kirillin et al., 2012). Three entire ice-covered periods were included in our results which could be used to investigate the thermal characteristics of Nam Co during the ice-covered season.

After the summer stratification ends, the autumnal overturn and hibernal stagnation period of an ice-covered lake could be divided into three sub-periods, namely, pre-winter, Winter I and Winter II, based on the thermal mixing characteristics (Kirillin et al., 2012). The rather homogeneous temperature of the entire water mass began to descend from ~5.5 °C to ~3.4 °C, which approached the T_{md} in late November and indicated the onset of the pre-winter period. The temperature continued to decrease because of heat loss from the surface until reaching a minimum of ~0.5 °C (even as low as 0 °C in 2012); then, the temperature increased again, and a typical inverse thermal stratification developed (Fig. 4). Because of the lake's large area and depth combined with the low temperature in the bottom of the lake during summer, the sediment-stored heat is very limited and has only very minor effects in Nam Co. Therefore, the Winter II phase should be predominant during most of the ice-covered season, during which radiative heating plays a major role in driving lake circulation (Kirillin et al., 2012).

Before freezing, the water temperature of the entire water column decreased to the T_{md} of ~3.4 °C because of intensive heat loss in early December (Fig. 4). Afterward, inverse stratification occurred because of further heat loss from the surface. After reaching its minimum values, the temperature of Nam Co began to continuously and synchronously increase in the entire water mass until the onset of stratification. A similar warming pattern was observed in 2012 and 2014 in terms of the timing of the coldest points and warm-up rate, but the pattern in 2013 was somewhat different. The coldest point in 2013 was approximately half a month earlier than those in the other two years, and the onset of stratification occurred between 5 days earlier than in 2012 and 5 days later than in 2014 (Table 2). Moreover, the minimum temperature and the temperature when the water began to stratify in 2013 were higher and lower than those in the other two years, respectively (Fig. 4). Thus, a longer warm-up period and lower temperature difference resulted in a less steep warming slope in 2013.

Gou et al. (2015) investigated changes in lake ice in Nam Co by using MODIS data and suggested that the onset of freezing in 2012/2013 was the latest compared to other years over the last 13 years (11 days later than the average) and that the ice melt duration was 10 days shorter than the average, which indicates that the water experienced a warmer winter. The lake ice phenology supported our result in terms of the increasing water temperature in the winter of 2012/2013. This phenomenon was very likely caused by differences in radiation or different amounts of snow cover on the ice, especially during the ice-covered period.

Table 1
Statistics of the water temperature (°C) and appearance time of observed extreme temperatures at different depths for station T2 from June 2013 to July 2014 (time format: yyyy/mm/dd hh:mm; temperature interval: 10 min).

Depth	Minimum	Appeared at	Average	Maximum	Appeared at
6 m	0.21	2014/1/13 8:50	5.53	12.06	2013/9/6 20:30
16 m	0.25	2014/1/17 6:20	4.96	11.85	2013/9/6 21:40
21 m	0.34	2014/1/14 20:50	4.50	11.84	2013/9/6 14:00
26 m	0.36	2014/1/14 19:50	3.89	11.62	2013/9/5 6:50
31 m	0.33	2014/1/22 10:10	3.52	9.30	2013/8/23 3:20
36 m	0.38	2014/1/22 10:00	3.36	7.41	2013/10/26 7:40
56 m	0.41	2014/1/22 11:50	2.94	7.07	2013/10/30 14:00
66 m	0.46	2014/1/21 18:50	2.89	6.63	2013/10/30 12:40

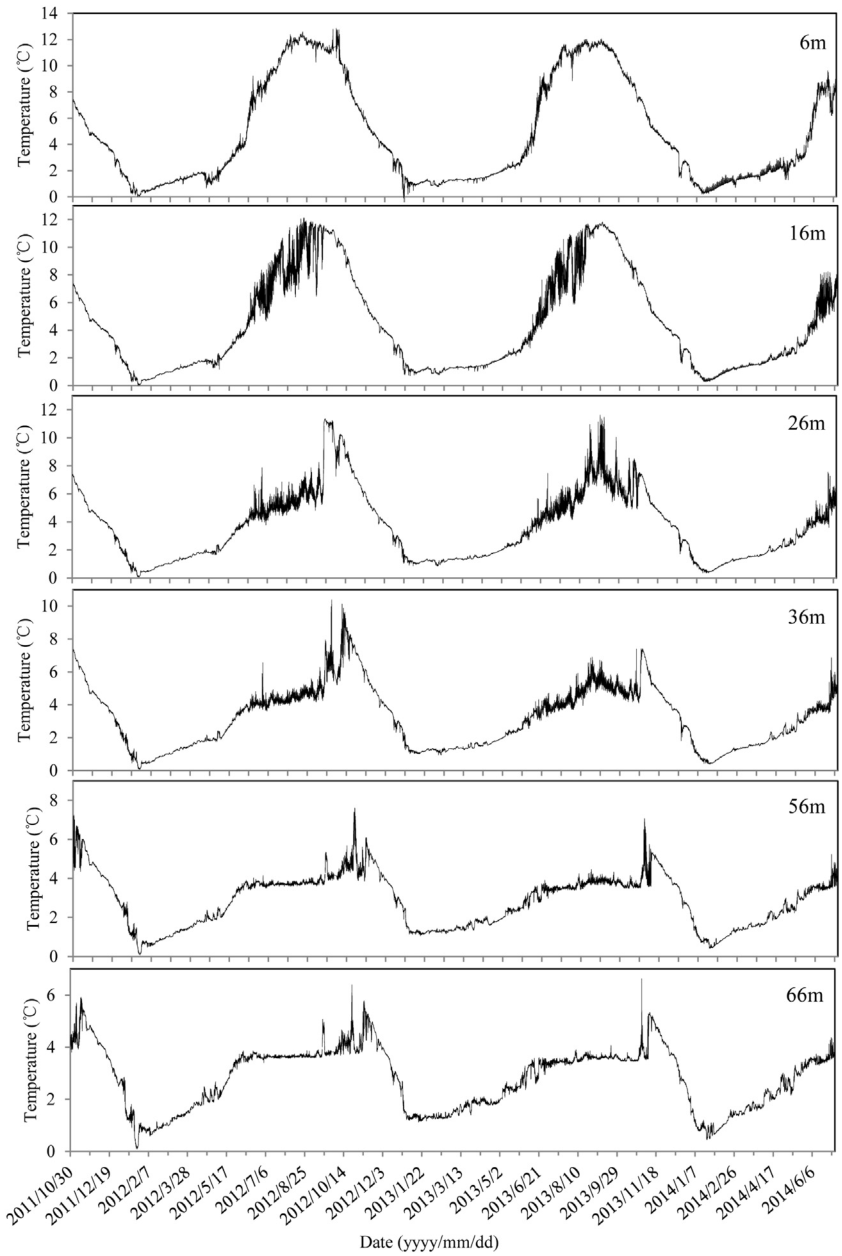

Fig. 6. Water temperature variation at selected depths during the entire study period with a 10-min interval at station T2.

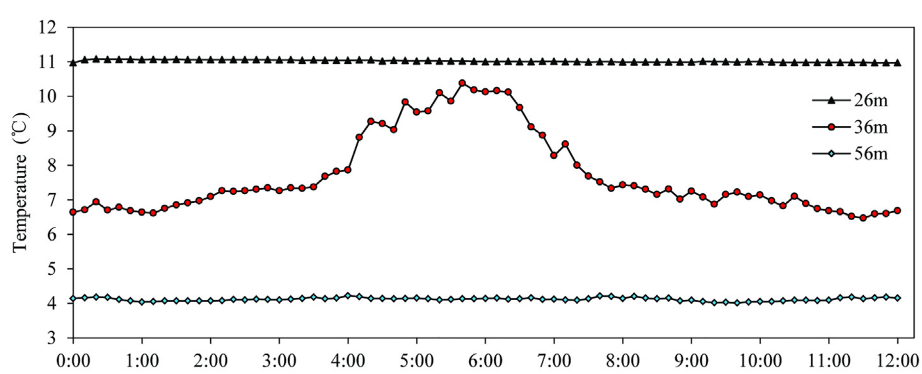

Fig. 7. Water temperature variation at selected depths on Sep. 25th, 2012 with a 10-min interval at station T2.

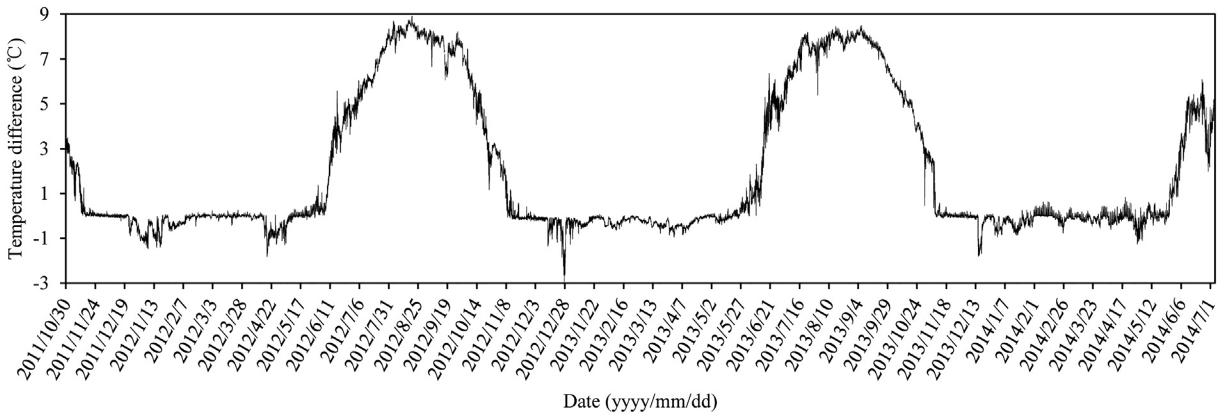

Fig. 8. Water temperature difference in the surface (6 m) and bottom (66 m) layers at station T2 in Nam Co during the study period (10-min interval).

Spatial difference of thermal stratification (stations T1 and T2)

Despite similar annual temperature patterns at stations T1 and T2 at Nam Co, variations in the temperature during transition periods, the overturn timing, and the timing of the formation and breakdown of thermal stratification could be observed (Fig. 2). After the lake ice melted, the lake water was still more or less homogeneous in mid-May of 2011, with temperatures between 2 and 3 °C at both stations (Fig. 2A). In mid-June of 2011, typical thermal stratification was observed at station T1 but not at T2 (Fig. 2B). In late October of 2011, the thermal stratification at T1 broke down and showed a homogeneous temperature of 8.1 °C. However, the water at T2 was still stratified, but the temperature of the epilimnion had decreased to 7.4 °C, and the epilimnion's thickness reached approximately 50 m (Fig. 2C). The thermal stratification regimes at station T1 and T2 were distinctly different. In more detail, the upper 40 m at station T1 had heated to >4 °C by the end of May of 2012 (approximately 8 °C at the surface), which indicates that thermal stratification had been established. Moreover, the distinct temperature increase at station T2 only occurred within the uppermost meter (Fig. 2D), even remaining <4 °C at the end of May of 2013 (Fig. 2H). In mid-July of 2012, a typical thermal stratification regime formed at station T2, and the thermal stratification pattern was similar to that of T1 but ~1 °C colder (Fig. 2E). During the same period of 2013, both stations showed an almost identical stratification regime, with a greater temperature gradient in the thermocline at T1 (Fig. 2J). The temperature at station T1 increased much earlier and faster; thus, the formation of a typical thermal stratification structure occurred approximately one month prior to that at station T2.

After thermal stratification was established at both stations, a similar structure that lasted almost two months in 2013 with a deepening trend in the thermocline was observed (Fig. 2J, K, and L). Then, the deepening at station T1 occurred faster than that at T2 until the thermal stratification disappeared at T1 and T2, respectively (Fig. 2F, C, and G). In mid-September of 2012, the epilimnion at both stations showed the highest water temperature of the year (~12 °C), and a thermocline was established at 34-m and 16-m depth at stations T1 and T2 with decreasing temperature gradients of 0.46 and 1.09 °C m^{-1} within the thermocline, respectively (Fig. 2F). This gradient was the maximum temperature gradient in the thermocline that was observed at station T2, while the maximum gradient of 1.57 °C m^{-1} at T1 occurred in mid-July of 2013 (Fig. 2J). The stratification at T2 disappeared around mid-November, which indicates that overturning began in this area (Fig. 4). The temperature was approximately 5 °C at T2 at the beginning of the mixing, which was distinctly lower than the overturning temperature of at least 8 °C at T1 (Fig. 4; Fig. 2C). Similar to the stratification's establishment, the breakdown of the thermal stratification at T1 occurred approximately one month earlier than that at T2.

Table 2
Onset and end date of thermal stratification (TS) at station T2 in Nam Co from 2011 to 2014.

Year	Onset of TS	End of TS	Duration of TS (days)
2011		12th, Nov	
2012	9th, Jun	9th, Nov	153
2013	4th, Jun	8th, Nov	157
2014	29th, May		

Many factors affect the thermodynamics in a lake. The lake morphometry, including the size, water depth/volume and shape/fetch, could be the most important factors because they affect the reaction of lake temperature to the heat fluxes between the lake water and the atmosphere. Nam Co is divided into two sub-basins (Fig. 1C). T1 is located in a small basin with shallower water depth. This small basin has a much smaller volume and lake area compared to T2, which results in lower thermal capacity and thus faster reaction times. During spring and autumn, the water body at T1 is more easily heated and cooled than that at T2.

During early spring, a “spring thermal bar” phenomenon regularly occurs in large dimictic lakes, which refers to different stratification regimes at both sides of the maximum density isotherm because of a faster increase in temperature in shallow areas compared to deeper waters (Rao and Schwab, 2007; Rao et al., 2004). Nam Co is a large dimictic lake, and a spring thermal bar likely developed between stations T1 and T2 before the water became stratified at T2 based on our results (Fig. 2). Station T1 showed a distinct earlier and faster temperature increase than T2, and the time difference in the thermal stratification's establishment at both stations was approximately one month. This duration of the spring thermal bar is somewhat consistent with what has been reported in the Great Lakes and other large lakes (~1–2 months) (Rao et al., 2004).

The thermal structure of lakes is also affected by the water clarity, which influences the depth of the epilimnion (Mazumder and Taylor, 1994) because the light penetration ability (transparency) affects heat transfer within the water body. In early June, during which the water temperature rose, the transparency (Secchi Disc depth) was approximately 6 m and 18 m at T1 and T2, respectively, under similar weather conditions (Table 3). Thus, the water temperature more easily increased in the upper part of T1 and thermal stratification formed earlier. Table 3 shows several sporadic measurements of transparency at stations T1 and T2 in different months. The largest difference in transparency occurred in early June when the stratification regimes were different, and the smallest difference was observed in mid-August when the stratification at both stations was strong and the stratification patterns were similar between the two stations (Fig. 2). This result showed that the

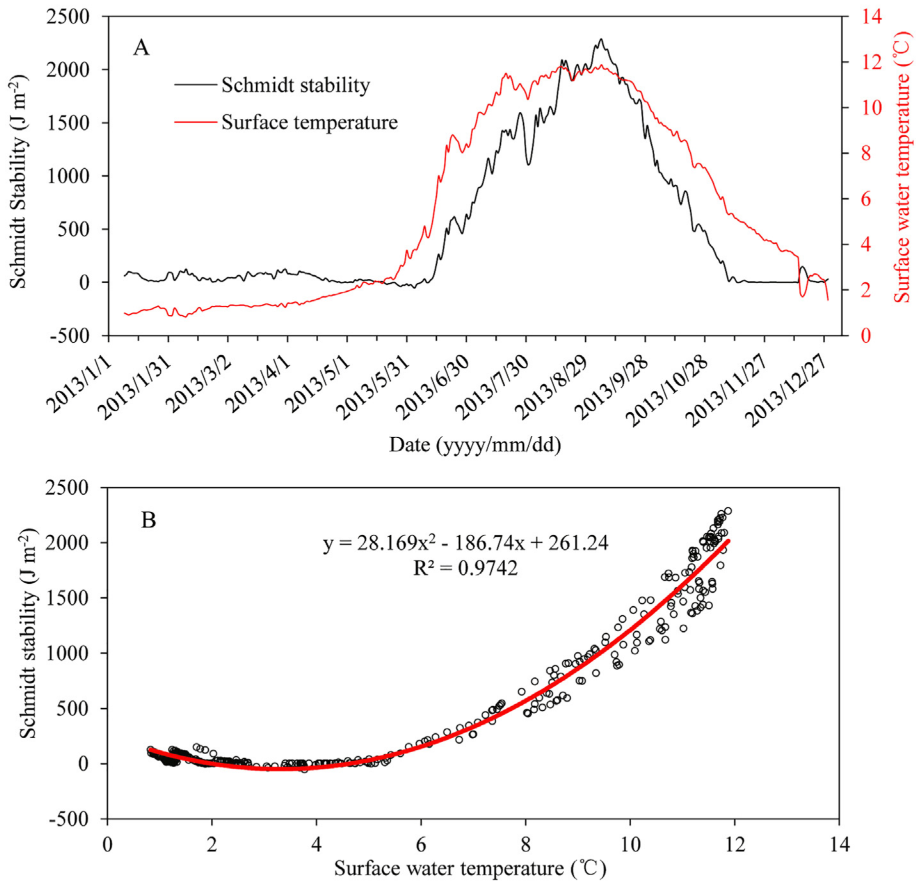

Fig. 9. Annual variation in the Schmidt stability of Nam Co (A) and the relation between surface water temperature and Schmidt stability (B) in 2013.

water transparency is likely an important factor that affects different stratification regime during the early stage of stratification formation.

Relationship between the surface water temperature and air temperature in Nam Co

The surface and epilimnetic water temperature of a lake can exhibit a rapid and direct response to climate forcing; consequently, the epilimnetic temperature could be used as an indicator of climate change (Adrian et al., 2009). The lake surface temperature (LST) is the most important characteristic because this variable directly responds to the lake's internal and external environment and determines the heat exchange between the lake and overlaying air. Many local factors, such as solar radiation, precipitation, runoff (including glacial meltwater), the prevailing wind direction, hot springs, and human activity such as sewage discharge, might be related and thus influence the LST to some extent over different time scales (Wang and Shi, 1980; Goldman and Horne, 1983; Wetzel, 2001).

When examining the relationships between the daily mean LST at T2 and different meteorological parameters for 2012 and 2013 in Nam Co, the results revealed that a similar trend was only found between the air

Table 3
Comparison of the water transparency as measured by a 30-cm Secchi disc (/ is no data) at stations T1 and T2 in Nam Co.

Measuring date	T1 (m)	T2 (m)
1st, June 2013	6	18
2nd, June 2013	/	16
14th, August 2013	12	13
8th, September 2013	11.6	/
28th, June 2014	10.7	13

temperature (Ta) and LST (Fig. 10), which suggests that both variables were mainly controlled by solar radiation. The air temperature exhibited a much larger annual variability than the LST, with the lowest and highest temperatures appearing in January and July, respectively, but the annual cycles of both temperatures showed similar trends in 2012 and 2013 (Fig. 10). No such high-frequency fluctuations in the LST occurred, as with the Ta, which reflects the modulation function of the lake water to air temperature changes. The LST was higher than the Ta during most of the year, while higher Ta only appeared during a short period between early May and mid-July, which correspond to the breakup of ice cover and the establishment of thermal stratification, respectively (Fig. 10).

Time series analysis of the LST and Ta indicated a pronounced temporal shift in the timing of the temperature maxima. This result indicates that a time lag effect existed, although the LST did follow variations in the Ta (Fig. 10). Some periods did exist during which no Ta data were available in both years. Thus, only data from a continuous period from Jan. 1st to Nov. 8th in 2012 were used to examine the correlation between the LST and Ta in Nam Co (Fig. 10A). The original dataset showed a correlation between both temperatures, but the linear relationship was rather poor (Fig. 11A). The time series were shifted in daily steps, and correlation coefficients were analyzed to quantify the time lag. The results showed an increasing correlation with increasing time shifts until the highest correlation coefficient of 0.9169 was reached with a shift of 38 days (Fig. 11B). The correlation coefficients were similarly >0.915 for time shifts from 34 to 40 days. This significant linear correlation between the LST and Ta after bias correction indicates that the LST responded well to the Ta with the described lag.

The relationship between the lake's surface water temperature and overlaying air temperature has been investigated in various areas and was used to predict the lake surface temperature by using air

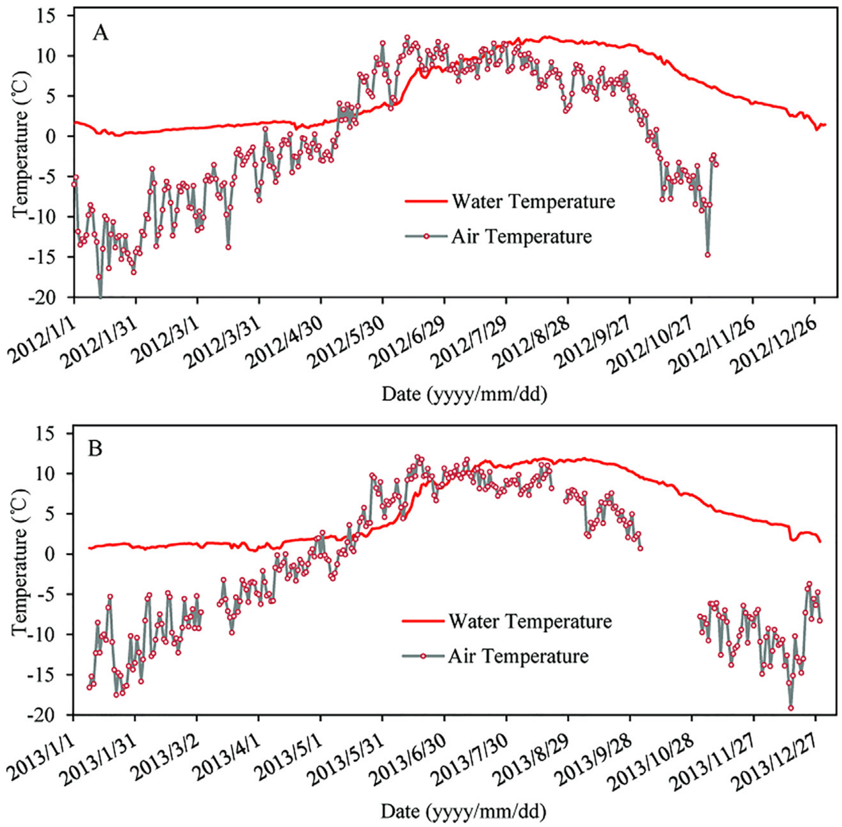

Fig. 10. Comparison of the daily mean surface water temperature and air temperature at station T2 in Nam Co in 2012 (A) and 2013 (B).

temperature (Livingstone and Dokulil, 2001; Livingstone and Lotter, 1998; Piccolroaz et al., 2013; Toffolon et al., 2014; Zhang et al., 2018). A distinct hysteresis of the LST to the Ta of 38 days was observed in Nam Co's main basin because of the thermal inertia and huge heat storage of the water volume (Fig. 11). The hysteresis pattern of Nam Co is similar to that of Lake Constance and Lake Baikal, which is likely influenced by the lake morphology (Toffolon et al., 2014). No hysteresis effect was observed at Ngoring Lake in northeastern TP (Li et al., 2015). A comparison of the LST and Ta showed remarkable seasonal variability. The LST responded much better to the Ta during the increasing temperature period than during the decreasing temperature period (Fig. 10). This result implies that the relationship between the LST and Ta is generally stronger during spring to early summer; moreover, the absolute values of both temperatures are likely to be consistent with each other in July. This result coincides well with that of a case study from Swiss Plateau, which was assumed to have a paleolimnological significance (Livingstone and Lotter, 1998).

Conclusions and perspectives

We presented a water temperature dataset of Nam Co that included two complete circulation cycles based on in situ measurements and the continuous monitoring of water temperature at two stations in two subbasins. Nam Co is classified as a dimictic lake, and some characteristics of thermal stratification were revealed. Nam Co is a typical lake on the central Tibetan Plateau in terms of its altitude, water depth and climatic conditions, so the results and findings that were presented in this paper have a broader significance for modern limnological and paleoenvironmental studies on the Tibetan Plateau.

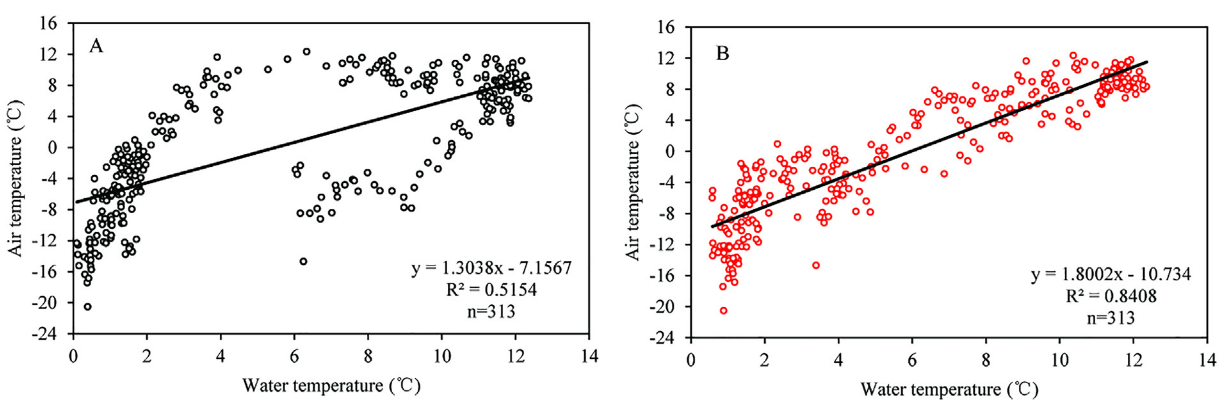

Fig. 11. Correlations between the daily mean surface water temperature and air temperature at station T2 in Nam Co (A) and the effect of a 38 lag of progression of water temperature (B) from January 1 to November 8, 2012, which reflects a hysteresis effect of 38 days.

A thermal stratification duration of approximately five months was identified in Nam Co, and different developing stratification regimes were distinguished in two sub-basins, which were likely caused by different water depths, transparency during spring and the probable presence of a spring thermal bar that moved from the shore towards the lake center. After the breakdown of thermal stratification, the water temperature abruptly decreased until it approached its lowest value (approximately 0.5 °C).

Abrupt short-term temperature fluctuations were observed at different depths during the entire monitoring period, some of which could be simultaneously detected within several layers. The amplitudes of these fluctuations could reach 3 °C within four hours, which shows the influence of internal waves. The lake surface temperature and local air temperature showed coherence with a distinct hysteresis effect of 38 days, which shows the significant effect of huge heat storage in such a large deep lake. A dataset of water temperature changes during ice-covered period supported this phenomenon in such a deep high-altitude lake.

Our observations, which included high-quality and high-resolution water temperature data that covered two entire annual thermal status cycles in Nam Co, enabled us to adequately investigate the relationship between the water temperature and local climate data. These data could be used to validate simulated water temperature changes by lake models and thus detect/reconstruct possible thermal stratification and evaporation changes in the past (e.g., Lazhu et al., 2016; Huang et al., 2017). Furthermore, this approach could be applied to predict potential thermal structure changes in Nam Co over a certain period in the future as driven by climate forcing data. This approach should greatly improve our understanding of lake status changes in such a pristine area and provide valuable information for policymakers to apply more feasible lake management and environmental protection strategies.

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