Contrasting hydrological and thermal intensities determine seasonal lake level variations – A case study at Paiku Co in the central Himalayas

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Abstract. Evaporation from hydrologically-closed lakes is one of the largest components of lake water budget, however, its effects on seasonal lake level variations remain unclear due to lack of comprehensive observations on the Tibetan Plateau (TP). In this study, lake evaporation at Paiku Co, central Himalayas, were investigated through energy budget method based on in-situ observations of lake thermal structure and hydrometeorology (2015-2018) and its effects on seasonal lake level variations are discussed. The results show that the seasonal pattern of heat flux over the lake surface was significantly affected by the large lake heat storage. Between April and July, about 66.5% of the net radiation was consumed to heat lake water. Between October and December, heat released from lake surface to the overlying atmosphere was about 3 times larger than the net radiation. There was ~5 month lag between the maximum lake evaporation and maximum net radiation. Lake evaporation at Paiku Co was estimated to be 975±96 mm during the ice free period (May to Dec), characterized by low values during the pre-monsoon and monsoon seasons and high values during the post-monsoon season. Contrasting hydrological and thermal intensities at Paiku Co play an important role in the seasonal lake level variations. Relatively low lake evaporation but high lake inflow led to rapid lake level increase during the summer monsoon season. In contrast, high lake evaporation and low lake inflow led to the dramatic lake level decrease during the post-monsoon season. While for shallow lakes, lake level does not exhibit large seasonal fluctuations due to the similar seasonal pattern of lake evaporation and lake inflow.

1 Introduction

The Tibetan Plateau (TP) hosts the greatest concentration of high-altitude inland lakes in the world. More than 1200 lakes (>1 km^2) are distributed on the TP, with a total lake area of more than 45000 km^2 in the 2010s (Ma et al., 2011; Zhang et al., 2014a). During the past decades, lakes on the TP experienced significant changes in response to climate warming and wetting, glacier mass loss and permafrost thawing (Lei and Yang, 2017). Most lakes on the interior TP expanded dramatically since the late 1990s, in contrast with lake shrinkage on the southern TP (e.g. Lei et al., 2013, 2014). For most lakes across the TP, lake water temperature increased (Zhang et al., 2014b; Su et al., 2019) and lake ice duration shortened considerably in response to rapid climate warming during the past decades (Kropacek et al., 2013; Ke et al., 2013; Cai et al., 2017).

Compared with numerous studies of inter-annual to decadal lake changes, seasonal lake level changes and the associated hydrological processes on the TP are still less understood. Phan et al. (2012) showed that seasonal lake level variations on the southern TP are much larger than that in the northern and western TP. In-situ observations gave more details of seasonal lake level variations (Lei et al., 2017). One striking feature is the different amplitude of seasonal water level variations, that is, deep lakes usually exhibited considerably greater seasonal lake level variations than shallow lakes. For example, Zhari Namco and Nam Co, two large and deep lakes on the central TP (Wang et al., 2009, 2010), exhibited significant water level increase by 0.3~0.6 m during the summer monsoon season and a similar magnitude of lake level decrease by 0.3~0.5 m during the post-monsoon season. For the two nearby small and shallow lakes, Dawa Co and Bam Co, although there was a similar pattern of lake seasonality, the amplitude of seasonal lake level variations was considerably smaller than the two large and deep lakes (Lei et al., 2017). The main causes of the different amplitude of seasonal lake level variations between deep and shallow lakes on the TP are still unclear.

Evaporation from hydrologically-closed lakes is one of the largest components of lake water budget (Li et al., 2001; Morrill, 2004; Xu et al., 2009; Yu et al., 2011). Direct measurements of lake evaporation were usually conducted through the eddy covariance system or energy budget method (Blanken et al., 2000; Winter et al., 2003; Rouse et al., 2003, 2008; Lenters et al., 2005; Rosenberry et al., 2007; Giannoiu and Antonopoulos, 2007; Zhang et al., 2014; Sugita, 2019). On the TP, there are several studies regarding lake evaporation using the eddy covariance system, e.g. Nogring Lake (Li et al., 2015), Qinghai Lake (Li et al., 2016), Nam Co (Wang et al., 2017, 2019), Siling Co (Guo et al., 2016). Results show that the seasonal pattern of lake evaporation is significantly affected by lake heat storage, especially for deep lakes. At Nam Co, for example, Haginoya et al. (2009) found that the sensible and latent heat fluxes were small during the spring and early summer, and increased considerably during the autumn and early winter due to the large heat storage. However, lake evaporation during the late autumn and early winter is not typically investigated through eddy covariance system because it is difficult to maintain the measurement platform due to the influence of lake ice on the TP. Although the energy budget method needs significant personnel commitment for fieldwork, it is more suitable for accurate, long-term monitoring of lake evaporation (Winter et al., 2003).

To quantify lake evaporation and its effects on seasonal lake level changes on the TP, we conducted comprehensive in situ observations at Paiku Co in the central Himalayas since 2013, including lake level, water temperature profile, runoff and hydrometeorology etc. In this study, lake evaporation at Paiku Co during the ice-free period is investigated through energy budget method and its effects on seasonal lake level variations are further discussed. We first address the thermal regime and changes in lake heat storage at Paiku Co based on three years' water temperature profile data (2015-2018), then investigate energy budget and heat flux over the lake surface, and finally analyse the seasonal pattern of lake evaporation and its impact on seasonal lake level changes.

2 Methodology

2.1 Site description

Paiku Co (85°35.12′ E, 28°53.52′ N, 4590m a.s.l) is located in the north slope of the central Himalayas. The lake has a surface area of 280 km^2 and watershed area of 2376 km^2. Bathymetry survey showed that Paiku Co has mean water depth of 41.1 m with the maximum water depth of 72.8 m (Lei et al., 2018). The lake is hydrologically closed and lake salinity is about 1.7 g/L. Glaciers are well developed to the south of the Paiku Co, with a total area of ~123 km^2. Dozens of paleo-shorelines are visible around Paiku Co. The highest shoreline is ~80 m above the modern lake level. Wünnemann et al. (2015) found that there was a close relationship between glacier dynamics and lake level changes since the Last Glacial Maximum (LGM). The lake has been shrinking since the 1970s (Nie et al., 2013; Dai et al., 2013). Between 1972 and 2015, lake levels at Paiku Co decreased by 3.7 ± 0.3 m and water storage reduced by 8.5 % (Lei et al., 2018). According to rain gauge data collected between 2013 and 2016, annual rainfall in the Paiku Co basin fluctuated significantly year to year. Typical annual precipitation varied between 150~200 mm, indicating that Paiku Co basin belongs to the dry belt in the northern slope of Himalaya mountains (Wang et al., 2019). The mean annual temperature was 4.4°C between June 2015 and May 2016 (Lei et al., 2018).

2.2 Data acquisition

In situ observations, including lake water temperature profile and hydrometeorology, were carried out in Paiku Co basin. HOBO water temperature loggers (U22-001, Onset Corp., USA) were used to monitor water temperature with an accuracy of ±0.2 °C. Two water temperature profiles were installed in Paiku Co's southern (0-42 m in depth) and northern (0-72 m in depth) basins (Fig. 1). In the southern basin, water temperature was monitored at the depths of 0.4 m, 5m, 10 m, 15 m, 20 m, 30 m and 40 m. In the northern basin, water temperature was monitored at the depths of 0.4 m, 10 m, 20 m, 40 m, 50 m, 60 m and 70 m. Since lake level fluctuates seasonally, the depth of water temperature loggers may also have changed in a range of 0.4-0.8 m. Water temperatures were recorded at an interval of 1 hour and daily-averaged values were used in this study.

Three years' observational data from June 2015 to May 2018 from the southern basin was acquired, while only one year's data (June 2016 and May 2017) from the northern basin was acquired.

>>Fig. 1<<

To investigate the local hydrometeorology at Paiku Co, air temperature and specific humidity over the lake were monitored since June 2015 using HOBO air temperature and humidity loggers (U12-012, Onset Corp., USA). The instrument has an accuracy of 0.35 ^{o}C for air temperature and 2.5% of relative humidity. Two loggers were installed in an outcrop ~2 m above the lake surface (Fig. 2). One is located in the north shoreline of Paiku Co, the other is located in the central shoreline of Paiku Co (Fig. 1). The instruments were under large rock where there was a hole facing the lake. It is not the ideal location where measurements should be made, but the measurements were used as a proxy of above-lake measurements and validation of this proxy will be discussed in section 4.1. There was no data available between February and May 2017 because the instrument battery was too low.

Radiation, including downward shortwave radiation and longwave radiation to lake, was measured by Automatic Weather Station (AWS) at Qomolangma station for Atmospheric Environmental Observation and Research, Chinese Academy of Sciences (CAS). This station (87°1.22′E, 28°25.23′N, 4276 m a.s.l) is located at the northern slope of Mount Everest, about 150 km east of Paiku Co. The 2 m air temperature, relative humidity, wind speed, radiation were recorded at an interval of 10 min. In this study, downward shortwave radiation and longwave radiation at this station were used because the climate conditions between Paiku Co and Qomolangma station were very similar, including topography, altitude, cloud cover etc. Nonetheless, weekly averaged lake evaporation was calculated in order to reduce the radiation error caused by regional difference. The related information about hydrometeorology observations at Paiku Co basin are listed in Table 1.

2.3 Energy budget derived lake evaporation

Lake evaporation was calculated using the energy budget (Bowen-ratio) method as described by Winter et al. (2003) and Rosenberry et al. (2007). The energy budget of a lake can be mathematically expressed as:

$$\mathrm{R} = \mathrm{H} + \mathrm{lE} + \mathrm{G} + \mathrm{S} + A_v \quad (1)$$

where R is the net radiation on the lake, H is the sensible heat flux from lake surface, lE is the latent heat utilized for evaporation, G is change in lake heat storage, S is the heat transfer between lake water and bottom sediment, and A_V is the energy advected into lake water. The units used for the terms of Eq (1) are $W \cdot m^{-2}$.

Av was estimated using total river discharge and the water temperature difference between river and lake. Lake water temperature was almost same to river water temperature between April and June, but 2-4^{o}C higher between July and December (data not shown). As a deep lake, total river discharge to Paiku Co was about 800-900 mm water equivalent to lake level and accounted for 2-2.5% of total lake water storage. The river discharge can accumulatively decrease lake water temperature by ~0.1 ^{o}C in a year. Therefore, as a deep lake, the influence of river discharge and precipitation on the total lake heat storage at Paiku Co is very small and can be neglected. Therefore, we do not consider the influence of G and A_V on the lake energy budget in this study.

The net radiation on the lake can be expressed as the following:

$$\mathrm{R} = R_s - R_{sr} + R_l - R_{\mathrm{l}r} - R_w \quad (2)$$

where R_s is downward shortwave radiation, R_{sr} is the reflection of solar radiation from lake surface, which is taken as 0.07 R_s in this study (Gianniou and Antonopouls, 2007), R_l is downward longwave radiation to lake, R_{lr} is the reflected longwave radiation from the lake surface, which is taken as 0.03 R_a, and R_w is the upward longwave radiation from lake. The units of the items in Eq (2) are $W \cdot m^{-2}$.

The upward longwave radiation from lake (R_w) is approached by the equation:

$$R_w = \varepsilon_a \times \sigma \times (T_w + 273.15)^4 \quad (3)$$

where σ is the Stefan-Boltzmann constant ($=5.67\times10^{-8}$ $W \cdot m^{-2} \cdot K^{-4}$), ε_a is the water emissivity (0.97 for water surface) and T_w is lake surface temperature (^oC). In this study, the water temperature at the depth of 0.4-0.8 m was used to represent the lake surface temperature. There exists surface warming during the day and surface cooling at night for high elevation lakes (Prats et al., 2018), thus the two uncertainties by surface warming and cooling can cancel each other at a temporal resolution of daily.

The sensible heat flux is related to the evaporative heat flux through the Bowen ratio (Henderson-Sellers, 1984):

$$\beta = \frac{H}{lE} = \gamma \times P \times \frac{T_w - T_a}{e_{sw} - e_d} \qquad (4)$$

where β is Bowen ratio, T_w is the surface water temperature (^oC), T_a is air temperature at 2m high above the water surface (^oC), e_{sw} and e_d are the saturated vapour pressure at the temperature of the water surface and the air vapour pressure above the water surface (kPa), respectively, P is air pressure (kPa), and γ is the psychrometric constant, 6.5×10^{-4} $^oC^{-1}$. In this study, air temperature, air pressure and specific humidity were monitored at the lake's shore. Saturated vapour pressure at the lake surface was calculated according to surface water temperature in the lake centre. To match the radiation, all the input data were averaged at weekly interval before lake evaporation was calculated.

Changes in lake heat storage (G) were calculated according to the detailed lake bathymetry and water temperature profile:

$$\mathrm{G} = \frac{\sum_{i=0}^{72.8} c_w \times \rho_w \times \Delta V_i \times \Delta T_i}{A_l} \quad (5)$$

where c_w is the specific heat of water ($J \cdot kg^{-1} \cdot K^{-1}$), ρ_w is water density ($=1000$ $kg \cdot m^{-3}$), ΔV_i is the lake volume at certain depth (m^3), and ΔT_i is water temperature change at the same depth, A_l is lake area (m^2). G was calculated at an interval of 5 m and therefore there are 13 layers in vertical direction. ΔV_i was acquired according to the 5m isobath of Paiku Co (Lei et al., 2018). ΔT_i was calculated at 5 m interval as the average temperature of the top and bottom layer. Changes in lake heat storage for the bottom water (>40 m) in 2015/2016 and 2016/2017 were calculated according to the data in 2016/2017 since there is no data in the other two years.

3 Results

3.1 Thermal structure of lake water

Water temperature profiles between 2015 and 2018 show that Paiku Co was thermally stratified between July and October, and fully mixed between November and June in each year of the study period (Fig. 2). Lake water temperature increased rapidly from 2 to 7 ^{o}C between April and June due to the strong solar radiation. During this warming period, water temperature between the lake surface and bottom was almost same, indicating the lake water was well mixed. The temperature gradient on vertical profile increased considerably in the late June and clear stratification occurred since July. The occurrence of thermal stratification corresponded to a significant reduction in wind speed (data not shown). Strong lake surface heating and the reduction in wind speed together contributed to the development of thermal stratification (Wetzel, 2001). During the summer stratification period, the surface water warmed rapidly from 7 to ~13 ^{o}C between July and August, while the bottom water warmed much more slowly. As a result, the surface water reached to its highest temperature in the late August while the bottom water (>40 m) reached to its highest temperature in the middle to late October. The thermocline formed between 15 m and 25 m water depth, with the largest temperature difference of 5~6 ^{o}C in the late August.

Lake surface temperature started to decrease gradually since September due to the decrease in solar radiation, however, the bottom water continued to warm slowly (Fig. 2). As a result, the water temperature gradient on vertical profile decreased, which weakened the lake stratification and deepened the mixed layer. The lake stratification totally broke down in the late October of each year, corresponding to significantly increased wind speed during this period (data not shown). Notably, the breakdown of stratification occurred gradually, with the mixed layer deepening gradually throughout October (Fig. 3). The mixed layer reached to 40 m water depth on October 13th, 2016, and to 70 m water depth about two weeks later (October 30th). Following the complete breakdown of the water column's stratification, the bottom water experienced rapid warming in several days due to its mixture with the warmer water from the upper layer. For example, the water temperature at 70 m water depth remained stable at ~6.9 ^{o}C from July to October, but increased abruptly from 6.9 to 8.6 ^{o}C in less than one week (October 25th to 30th). Paiku Co's water column was fully mixed since November as indicated by the identical lake water temperature profiles at the two monitoring sites (Fig. 2, Fig. 3). Water temperature of the whole lake decreased gradually from 8.6 to 1 ^{o}C from November to January and remained stable at 1-2 ^{o}C until March.

The thermal structure indicates that Paiku Co is a dimictic lake, which is similar to Bangong Co (Wang et al., 2014) and Nam Co (Wang et al., 2019), but different from Dagze Co (Wang et al., 2014). The water temperature gradients at Paiku Co and other lakes on the TP are considerably lower than those in other parts of the world (Livingstone, 2003; Stainsby et al., 2011, Zhang et al., 2015), which is probably due to the low lake surface temperature in summer in this high elevation area.

>>Fig. 2<<

>>Fig. 3<<

3.2 Energy budget over the lake surface

The main components of energy budget over the lake surface, including downward shortwave radiation, downward longwave radiation to lake and upward longwave radiation from the lake body, are shown in Fig. 4a-c. Downward shortwave radiation had an annual average of 251.8 W·m^{-2} (Fig. 4), which is slightly higher than the TP average due to its lower latitude (Yang et al., 2009). Downward and upward longwave radiation over the lake surface had an annual average of 235.8 W·m^{-2} and 336.8 W·m^{-2}, respectively. The net radiation over Paiku Co varied seasonally in a range of 19.0~212.1 W·m^{-2}, with an average value of 125.8 W·m^{-2}. Relatively high net radiation occurred from April to August (200.4 W·m^{-2}), with the highest value in June (212.1 W·m^{-2}). Relatively low net radiation occurred from October to February (52.2 W·m^{-2}), with the lowest value in December (19.7 W·m^{-2}).

>>Fig. 4<<

Changes in lake heat storage at Paiku Co were quantified using in-situ observations of water temperature profile and detailed lake bathymetry (Fig. 4e), which makes it possible to evaluate the impact of lake heat storage on the heat flux over the lake surface. Between April and July when Paiku Co warmed gradually, the lake water absorbed energy at an average rate of 128.6 W·m^{-2}, accounting for 66.5% of the net radiation during the same period. The lake heat storage increased most rapidly in June, with an average rate of 191.6 W·m^{-2}, accounting for 91.6% of the net radiation during the same period. The lake heat storage reached its peak in the late August, when the surface water temperature was in its highest. Between October and January, when the lake water cooled, the lake released energy to the overlying atmosphere at an average rate of 137.5 W·m^{-2}, which was more than 3 times larger than the net radiation during the same period. The lake heat storage decreased most rapidly in November at an average rate of 193.6 W·m^{-2}, which was about 5 times larger than the net radiation during the same period.

3.3 Lake evaporation

Latent and sensible heat fluxes at Paiku Co were determined using Bowen ratio method. The Bowen ratio varied in a range of -0.26~+0.37 (Fig. 5c). Negative values occurred between April and July, with an average value of -0.12. Positive values occurred between August and December, with an average value of +0.20. Latent heat flux was the main component of heat flux, with an average value of 112.3 W·m^{-2} between May and December. The latent heat was in low values between May and June, with an average of 38.7 W·m^{-2}. High values occurred between October and December, with an average of 153.3 W·m^{-2} (Tab. 2). Latent heat flux at Paiku Co is positively correlated with the water vapour pressure difference between the lake surface and the overlying atmosphere (r^2=0.41, $P<0.001$). Sensible heat flux has an annual average value of 13.3 W·m^{-2}, accounting for ~11% of latent heat flux. Sensible heat flux was negative between April and July with an average value of -5.6 W·m^{-2} (Tab.2), and was in positive value between August and December with an average of 23.0 W·m^{-2}. The sensible heat was positively correlated with the water temperature difference between surface water and the overlying atmosphere (r^2=0.86, P<0.001).

>>Fig. 5<<

Lake evaporation at Paiku Co during the ice-free season is shown in Fig. 6b. Lake evaporation was generally low in May and June with an average value of 1.7 mm/day. In July and August, lake evaporation increased rapidly from 2.9 to 4.1 mm/day. High lake evaporation occurred between September and December, with an average value of 5.4 mm/day. The total lake evaporation was estimated to be 975 mm between May and December during the study period. Lake evaporation between January and April is not determined because part of the lake surface was covered by lake ice during the study period.

>>Fig. 6<<

Lake evaporation at Paiku Co lagged net radiation by ~5 months and exhibited a similar seasonal pattern with changes in lake heat storage. Regression analysis shows that lake evaporation at Paiku Co positively correlated with changes in lake heat storage (r^2=0.63), but negatively correlated with net radiation (r^2=0.22), which indicating that the seasonal pattern of lake evaporation is significantly affected by lake heat storage. When the net radiation was high between May and July, most of the energy is used to heat the lake water and only a small part of it is consumed as the latent heat flux. When the net radiation was low between October and December, a large amount of heat was released from the lake water as latent heat to the overlying atmosphere. Lake evaporation exhibited similar patterns with the water vapour pressure difference between surface water and the overlying atmosphere (r^2=0.33).

3.4 Contrasting hydrological and thermal intensities determine seasonal lake level variations

Fig.6a shows that there is contrasting pattern of hydrological and thermal intensities at Paiku Co. Precipitation and lake inflow were mainly concentrated during the summer monsoon season (Jul and Aug), while lake evaporation was relatively low during this period (Fig. 6b, c), which together led to positive lake water budget and the rapid lake level increase (40~60 cm) at Paiku Co. During the post-monsoon season (Oct to Dec), precipitation and lake inflow were already very low, while lake evaporation was in its high value, which led to negative lake water budget and the rapid lake level decrease (~40 cm). Contrasting hydrological and thermal intensities play an important role in the large amplitude of seasonal lake level variations.

Lake evaporation can largely determine the amplitude of lake level changes in dry seasons. Paiku Co's lake level decreased considerably at a rate of 3.8 mm/day on average during the post-monsoon season (Oct to Dec), which is in contrast to the slight decreasing rate of 1.3 mm/day during the pre-monsoon season (May) (Fig.6, Lei et al., 2018). So, what is the main cause of the different rate of lake level decrease during the two dry seasons? Runoff measurements at the three main rivers feeding Paiku Co indicate that the surface runoff had a weak impact on lake level changes during the two dry seasons (Tab. 3). The seasonal pattern of lake evaporation can explain this well. High lake evaporation during the post-monsoon season led to the rapid lake level decrease, while low lake evaporation during the pre-monsoon season led to much lower lake level decrease.

In a larger sense, Lei et al (2017) investigated the lake level seasonality across the TP and found that there were different amplitudes of lake level fluctuations even in similar climate regimes. For example, lake level at Nam Co and Zhari Namco, two large and deep lakes on the central TP (Wang et al., 2009, 2010), decreased considerably by 0.3-0.5 m in post-monsoon season (Fig. 7), while lake level at two nearby small lakes, Bam Co and Dawa Co, decreased slightly by 0.1-0.2 m during the same period. Different lake heat storage can play an important role in the amplitude of lake level seasonality. For deep lakes (e.g. Paiku Co, Nam Co and Zhari Namco), the latent heat flux (lake evaporation) over lake surface may lag the solar radiation by several months due to the large heat storage. For this kind of lake, the lake level drop mainly occurs during the post-monsoon season when lake evaporation is high but lake water input is already very low. For shallow lakes, the latent heat flux closely follows solar radiation, namely high lake evaporation occurs during the pre-monsoon and monsoon seasons, and low lake evaporation occurs during the post-monsoon season (Morrill et al., 2004). Meanwhile, shallow lakes freeze up 1-2 months earlier than deep lakes. When the lake surface is covered by ice, lake evaporation (mainly through sublimation) can be significantly reduced (Huang et al., 2019). Consequently, lake level decreased more slowly in the post-monsoon season in shallow lakes than that in deep lakes. This phenomenon can also be seen in some thermokarst lakes on the northern TP (Luo et al., 2015; Pan et al., 2017).

>>Fig. 7<<

4 Discussion

4.1 Uncertainty of lake evaporation estimation

In this study, uncertainty of lake evaporation can be mainly caused by the following factors, net radiation, meteorological data (air temperature and humidity), lake surface temperature and changes in lake heat storage. The first factor causing uncertainty of lake evaporation is the determination of solar radiation and atmospheric long wave radiation. Solar radiation and atmospheric longwave radiation at Qomolangma station were used to represent values at Paiku Co. To evaluate the spatial difference, we made a comparison of solar radiation at Paiku Co and Qomolangma Station by using Hamawari-8 satellite data (Tang et al., 2019; Letu et al., 2020). The results show that daily solar radiation at the two sites exhibited very similar seasonal fluctuations (R^2=0.55, P<0.001), with RMSE of 23.9 $W \cdot m^{-2}$ (9.5% of solar radiation).

The second factor is the uncertainty of meteorological data. Meteorological data at the shoreline (air temperature and relative humidity) is used to calculate lake evaporation. To check its representativeness, we made a comparison of meteorological data between shoreline and lake centre. We set up a platform in the southern centre of Paiku Co in September 2019 (water depth: 19 m; least distance from shoreline: 2 km) and a simple AWS station (GMX600) was installed on the platform. Meteorological data between September 22nd and October 26th were acquired and compared with that from shoreline. Results show that both air temperature and relative humidity fluctuated very similarly between the shoreline and lake centre (Fig. 8), indicating the meteorological data from the shoreline of Paiku Co can be used to represent the general condition of the whole lake at least during the observed period. Unfortunately, the platform was damaged by lake ice in the winter of 2019/ 2020.

Here the RMSE of air temperature and water vapour pressure in the shoreline are estimated to be 0.91 ^{o}C and 0.069 kPa by using those in the lake centre as true value.

>>Fig. 8<<

The third factor is the uncertainty of lake surface temperature. In this study, lake water temperature at the depth of 0.4-0.8 m, not lake skin temperature is used to calculate Bowen ratio and lake evaporation. Studies show that lake skin temperature is higher than surface water temperature during daytime, and vice versa in nighttime (Prats et al., 2018). Here MODIS derived lake surface temperature data is used to determine the difference between the two dataset (data now shown). In spring and summer when the lake water gets warm, the skin temperature derived from MODIS data is about 1.2 ^{o}C higher than lake body temperature. In autumn and winter when the lake water gets cool, the skin temperature derived from MODIS data is about 0.05 ^{o}C higher than lake body temperature. Therefore, the difference between lake surface temperature and in-situ observation is estimated to be 0.6 ^{o}C for a whole year.

The fourth factor is the uncertainty of changes in lake heat storage. Changes in lake heat storage are determined by lake water storage and lake water temperature profile. Uncertainty of lake water storage mainly results from the measured water depths, interpolation algorithms, volume calculation methods, etc. The depth sounder measured the water depth at an accuracy of 1%, and the maximum water depth of Paiku Co is 70 m. Using method of Qiao et al. (2018), uncertainty of lake water storage estimation at Paiku Co was estimated to 6% by comparing the reconstructed lake level and ICESat and CryoSat-2 satellite altimetry data between 2003 and 2018.

Uncertainty of total lake evaporation is estimated by comparing lake level changes during the pre-monsoon and post-monsoon seasons when the runoff is low. Runoff measurements at the three large rivers feeding Paiku Co are shown Tab. 3. During the pre-monsoon season (May), lake evaporation (1.7 mm/day) is similar with the rate of lake level decrease (1.8 mm/day). During the post-monsoon season (Oct to Dec), lake evaporation (5.4 mm/day) is considerably higher than the rate of lake level decrease (3.8 mm/day). This discrepancy (1.6 mm/day) may be partly due to the contribution of precipitation and surface runoff. As shown in Table 3, runoff at the three large rivers can contribute to lake level increase by 1.2 mm/day on average in October, thereby partially offsetting lake level changes from lake evaporation. According to the difference between lake evaporation and the sum of lake level decrease and runoff (0.4 mm/day), the total error of lake evaporation is estimated to be 96 mm during the entire ice-free period (May to Dec).

4.2 Comparison with other lakes on the TP

The quantification of lake evaporation is important for understanding lake water budget and associated lake level changes. Compared with the eddy covariance system that can only work until October/November when the lake surface begins to freeze (Li et al., 2015; Wang et al., 2017; Guo et al., 2016), our results give a full description of lake evaporation during the entire ice-free period. More importantly, our results indicate that for deep lakes on the TP, evaporation during the post-monsoon season can be much higher than that during the pre-monsoon seasons due to the release of large amount of stored heat (Haginoya et al., 2009), despite both air temperature and net radiation are already much lower. In this sense, lake evaporation during the cold season (October to December) is of great importance to lake water budget and can significantly affect the amplitude of lake level changes, especially for deep lakes.

To further explore the impact of lake heat storage on the seasonal pattern of lake evaporation, we compared lake evaporation at Paiku Co with other lakes on the TP. We only selected lakes with direct measurements of lake evaporation, including the eddy covariance system or energy budget method. At Ngoring Lake (area, 610 km^2; mean depth, 17 m) on the eastern TP, Li Z. et al. (2015) investigated the lake's energy budget and evaporation in 2011-2012 using the eddy covariance system, and found that the latent heat at Nogring Lake was lowest in June, peaked in August and then decreased gradually from September to November. At Qinghai Lake (area, 4430 km^2; mean depth, 19 m) on the northeast TP, Li X. et al. (2016) conducted studies concerning the lake's energy budget and evaporation in 2013-2015 using the eddy covariance system, and found that there was a 2–3 month delay between the maximum net radiation and maximum heat flux. Compared with Paiku Co, we can find that there was shorter time lag between the heat flux and net radiation at the two shallower lakes. As we have shown, Paiku Co has the mean water depth of ~41 m and the water column is fully mixed between November and June. This means that deep lakes like Paiku Co can store more energy in spring and summer than relatively shallow lakes, and can release more energy to the overlying atmosphere in the post monsoon season.

At Nam Co, a large and deep lake on the central TP, there have been several studies regarding lake evaporation (Haginoya et al., 2009; Ma et al., 2016; Wang et al., 2017, 2019). Haginoya et al. (2009) found that lake evaporation at Nam Co was lowest in May and highest in October. Lake evaporation at Nam Co was estimated to be 916~986 mm through Bowen ratio method (Lazhu et al. 2016) and eddy covariance system (Wang et al., 2019). Comparison with Paiku Co shows that lake evaporation at both lakes exhibited similar seasonal variations, although it was slightly larger at Paiku Co than that at Nam Co due to its higher solar radiation. In fact, although the maximum depth at Nam Co is greater than that at Paiku Co, the average water depth of the two lakes is similar (Wang et al., 2009; Lei et al., 2018), which resulted in similar seasonal pattern of lake evaporation. At Siling Co, another large and deep lake on the central TP, monthly lake evaporation was found to vary within a range of 2.4-3.3 mm/day between May and September, 2014, with a total amount of 417.0 mm during the study period (Guo et al., 2016). Although the accumulative evaporation between Paiku Co and Siling Co was similar between May and September, lake evaporation at both lakes during the post-monsoon season can not be further compared because the energy flux at the lake was not measured at Siling Co.

5 Conclusion

Lake evaporation and its impact on seasonal lake level changes at Paiku Co in the central Himalayas were investigated based on three years' in-situ observations of lake water temperature profile and hydrometeorology. The results show that Paiku Co is a dimictic lake with clear lake stratification occurring between July and October. The surface water reached to its highest temperature in late August while the bottom water reached to its highest in two months late (middle to late Oct.). The thermocline formed between 15 m and 25 m water depth, with the largest temperature difference of 5~6 ^{o}C in late August.

As a deep alpine lake, lake heat storage significantly affected the seasonal pattern of energy budget and lake evaporation. The lake absorbed most of net radiation to heat the lake water in the spring and early summer and released it to the overlying atmosphere in autumn and early winter. Between April and July, about 66.5% of the net radiation was consumed to heat the lake water. Between October and January, heat released from lake water was about 3 times larger than the net radiation. As a result, there was ~5 month lag between the maximum heat fluxes and the maximum net radiation due to the large heat storage of lake water. Lake evaporation at Paiku Co was estimated to be 975±96 mm between May and December, with low values between May and June (1.7 mm/day), and high values between October and December (5.4 mm/day).

Our result may have significant implications for understanding the different amplitude of seasonal lake level variations between shallow and deep lakes. For deep lakes like Paiku Co, high lake evaporation and low lake inflow lead to the dramatic lake level decrease during the post monsoon season. In contrast, relatively low lake evaporation but high lake inflow led to rapid lake level increase during summer monsoon season (Jun to Aug). Contrasting hydrological and thermal intensities determines the large amplitude of seasonal lake level variations. For shallow lakes, the seasonal pattern of lake evaporation varies similarly with the net solar radiation, which results in slight lake decrease in post-monsoon season and less amplitude of lake level seasonality.

Data availability

All original data presented in this paper are publicly available via National Tibetan Plateau Data Center (http://data.tpdc.ac.cn/en/).

Author contribution

LeiY.B. and Yao T.D. conceived and designed the experiments; Lei.Y., YaoT.D., Yang K., Lazhu, and Ma Y.M. analyzed the data; LeiY.B. performed the fieldwork and wrote the paper; Bird B.W. helped write the paper.

Competing interests

The authors declare that they have no conflict of interest.

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Figure and Captions

Table 1 The related information about hydro-meteorology observations

Parameter	Sensor	Accuracy	Location	Duration
T_w	HOBO U22-001	0.21 °C	South center	2015.6-2018.5
			North center	2016.6-2017.5
T_a and RH	HOBO U12-012	0.35 °C 2.5%	Shoreline	2015.6-2017.1, 2017.6-2018.5
T_a and RH	GMX600	0.1 °C 1%	South center	2019.9-2019.10
R_s and R_l	Kipp & Zonen CNR4 net radiometer	5%	Qomolangma Station, CAS	2015.6-2017.12

T_w=water temperature; T_a=air temperature; RH=relative humidity; R_s=shortwave solar radiation; R_l=downward long wave radiation

Table 2 Monthly net radiation, total lake heat storage, Bowen ratio and lake evaporation between 2015 and 2017

Month	Net energy (W·m^{-2})			Heat storage (W·m^{-2})			Bowen Ratio			Evaporation (mm/day)		
	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017
May		188.5	194.8		145.2	138.6		-0.10			1.72	
Jun	217.2	214.3	224.8	157.3	191.6	181.8	-0.15	-0.24	-0.20	2.40	0.98	1.81
Jul	198.0	185.2	218.1	123	101.0	93.4	-0.02	0	-0.04	2.6	2.89	3.28
Aug	170.4	178.6	177.2	62.3	32.4	39.3	0.11	0.13	0.11	3.33	4.47	4.31
Sep	148.4	140.2	154.1	-24.6	-10.7	-15.4	0.13	0.14	0.08	5.29	4.57	5.40
Oct	89.1	91.4	92.4	-115	-87.1	-86.4	0.23	0.20	0.20	5.67	5.12	5.15
Nov	34.7	34.9	34.3	-140.6	-193.7	-199.5	0.17	0.18	0.24	5.12	6.69	6.51
Dec	17.7	16.6	19.7	-192	-125.3	-148.5	0.26	0.14	0.20	5.78	4.22	4.88

Table 3 Runoff (m^3/s) at the three main rivers at Paiku Co basin in spring and autumn between 2015 and 2017 and their total contribution to lake level increase (mm/day).

Rivers	Runoff-2015		Runoff-2016		Runoff-2017	
	Spring (6.1~6.2)	Autumn (10.6~10.7)	Spring (6.2)	Autumn (10.11~10.13)	Spring (5.25~5.28)	Autumn (10.14~10.16)
Bulaqu	2.3	2.1	0.8	0.7	0.5	0.7
Daqu	0.4	2.8	1.1	1	0.5	1.2
Barixiongqu	0.2	0.4	0.1	0.5	0.1	0.5
Total contribution	0.89	1.64	0.62	0.71	0.62	0.74

Total contribution is calculated according to the total runoff of the three main rivers and lake area. The measuring dates are shown in brackets.

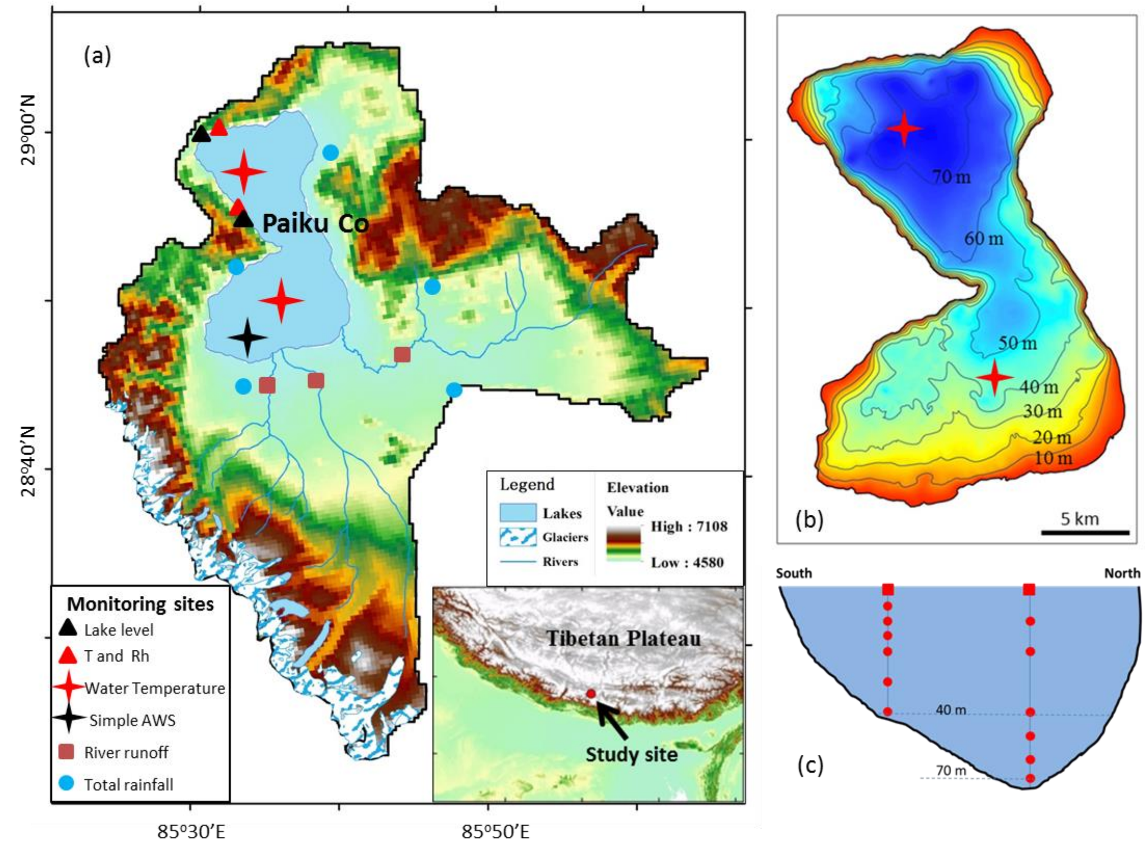

Figure 1: Monitoring sites of lake water budget at Paiku Co basin. (a): Monitoring sites of lake level, hydro-meteorology, water temperature profile, runoff, and total rainfall. (b): The isobath of Paiku Co and the two monitoring sites of water temperature profile. (c): The water temperature monitoring at different water depths.

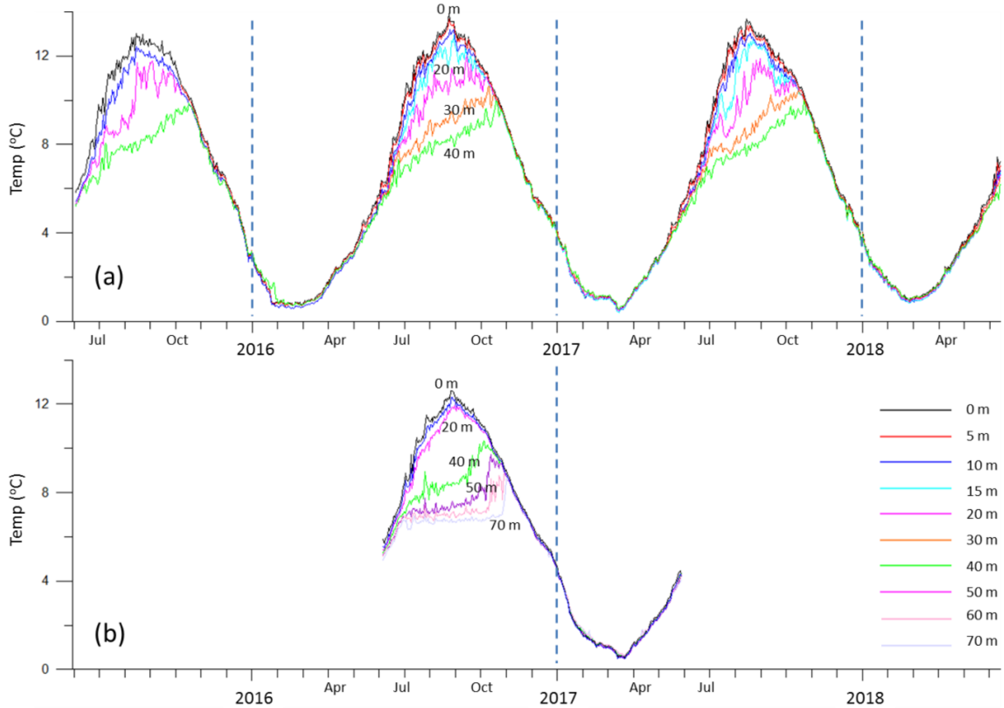

Figure 2: Time series of daily lake water temperature at different water depths in Paiku Co's southern (a) and northern (b) basins.

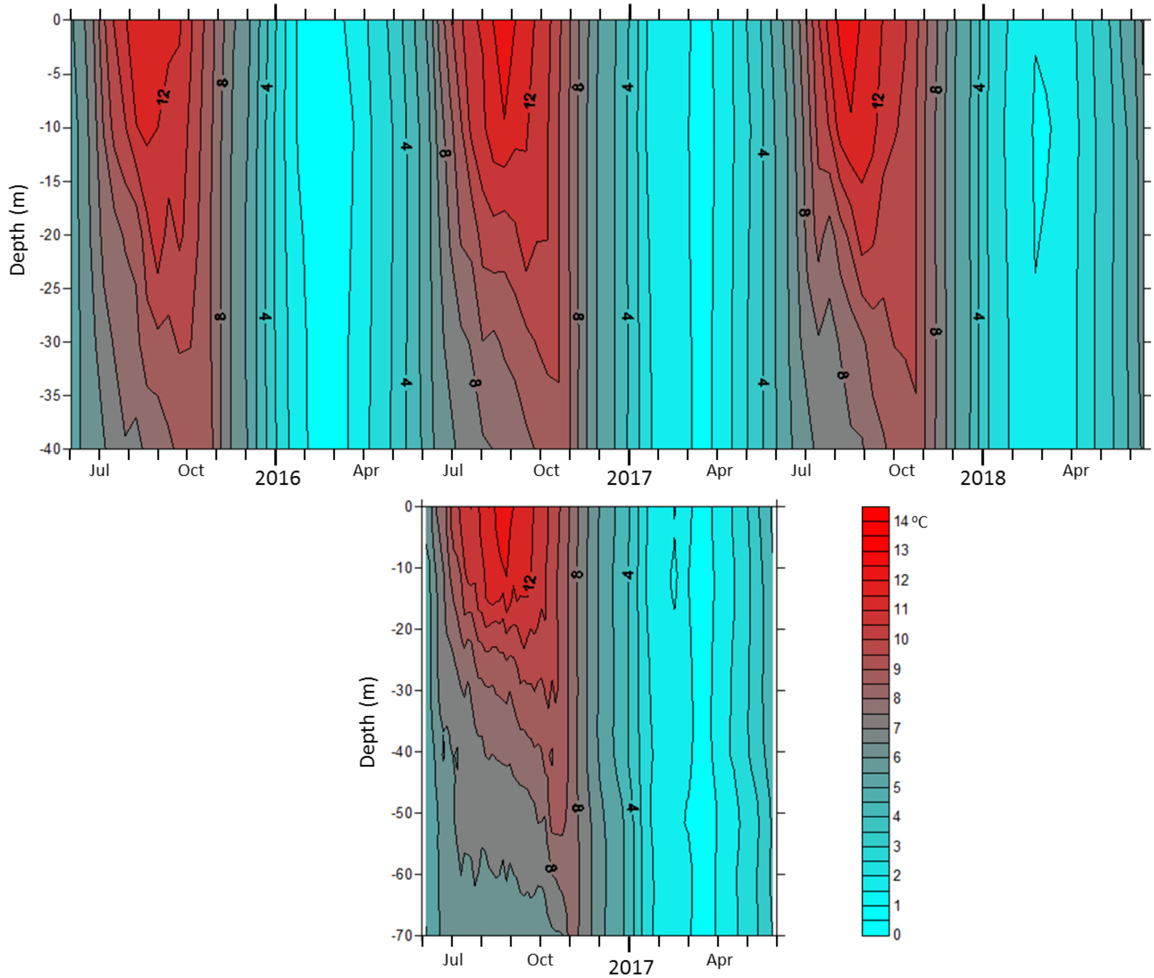

Figure 3: Depth-time diagram of isotherm (°C) in Paiku Co's southern (upper, 42 m in depth) and northern (below, 72 m in depth) basins between June 2015 and May 2018.

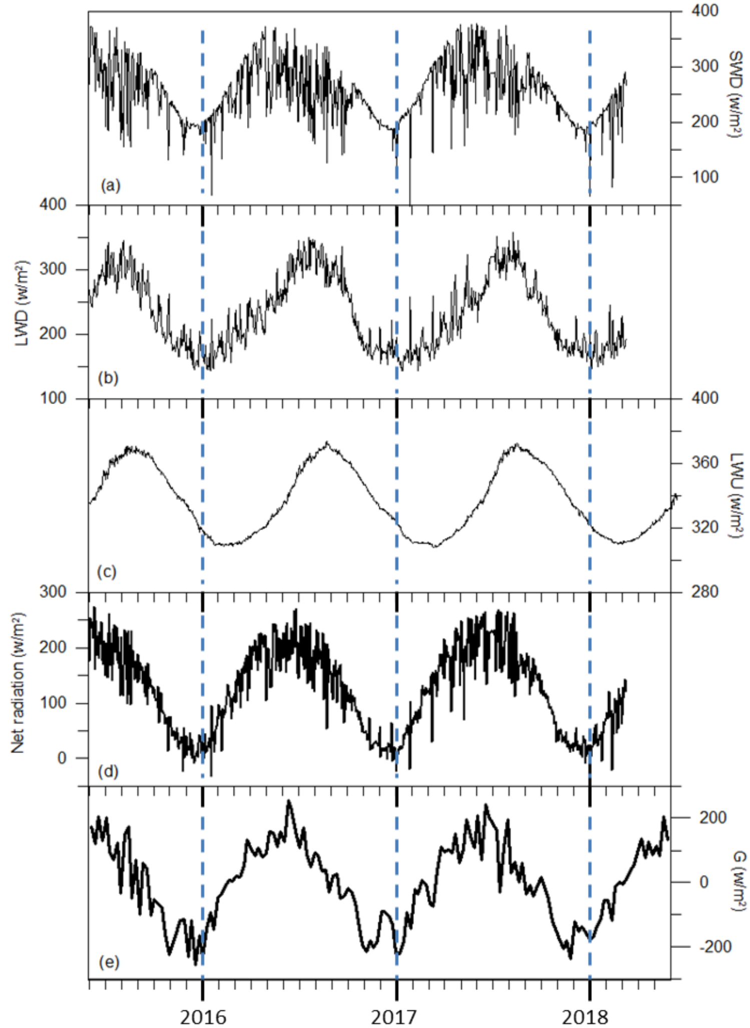

Figure 4: The main components of energy budget at the lake surface and changes in lake heat storage. (a): Downward short wave radiation, (b): Atmospheric long wave radiation to lake, (c): Long wave radiation emitted from lake, (d): Net radiation, (e): Weekly changes in lake heat storage (G).

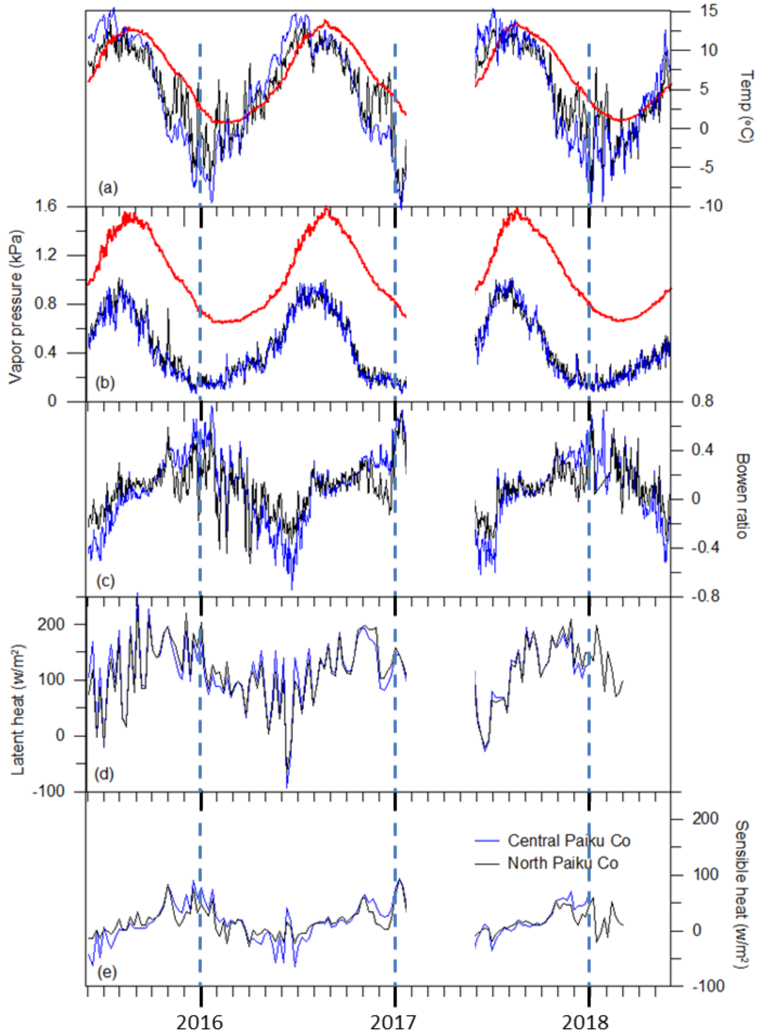

Figure 5: Hydrometeorology and heat flux at the lake surface. (a): Air temperature and daily surface water temperature (red line), (b): Actual vapour pressure at lake surface (red line) and the overlying atmosphere, (c): Bowen ratio, (d-e):Weekly latent and sensible heat flux at the lake surface. For a-e, black lines denote north Paiku Co and blue lines denote central Paiku Co. There was no data available between February and May 2017.

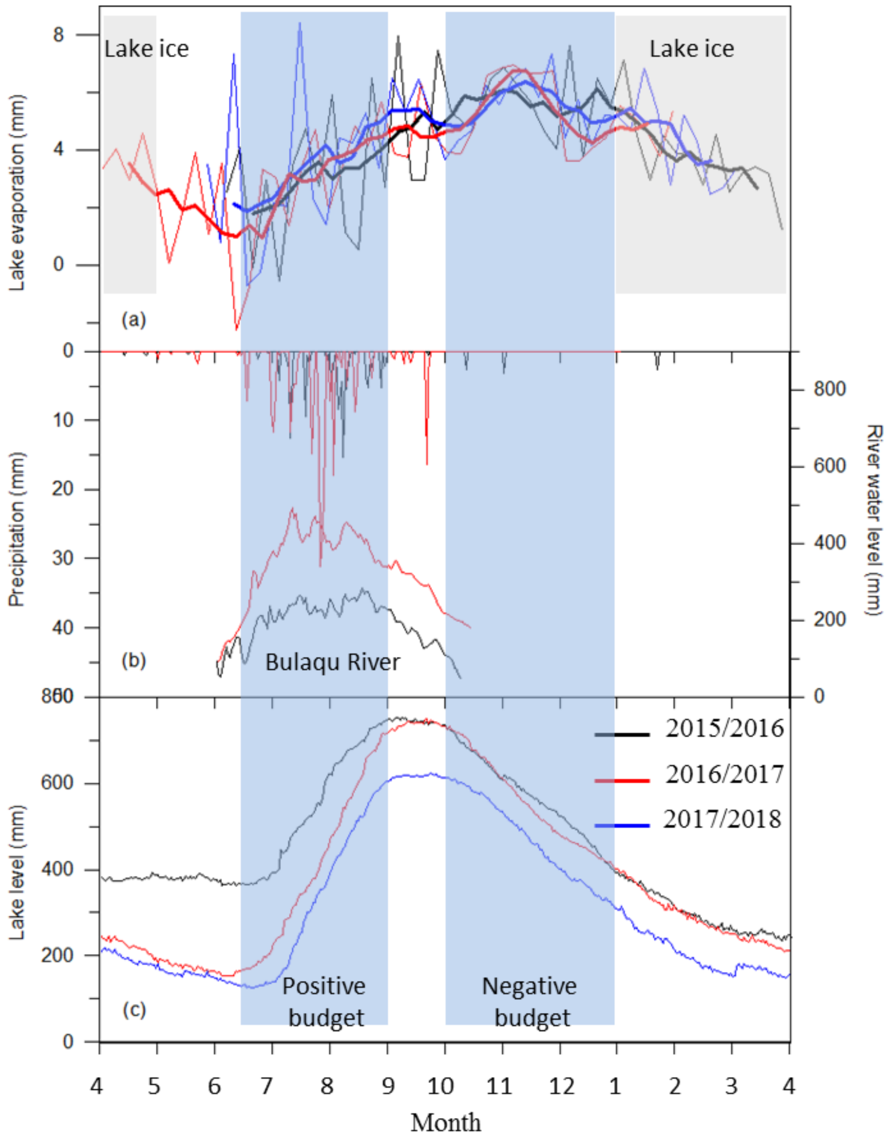

Figure 6: The main components of lake water budget at Paiku Co. (a): Weekly lake evaporation derived from the north shoreline of Paiku Co. (b): Precipitation at Qomolangma station and water level of Bulaqu River in 2015 and 2016. Note the Y axis (left) of precipitation is reversed. (c): Seasonal lake level variations of Paiku Co. The thick lines (a) denote the 5-point running average. The grey rectangles represent the ice-covered period and the blue ones are two periods of positive and negative lake water budget in monsoon and post-monsoon seasons.

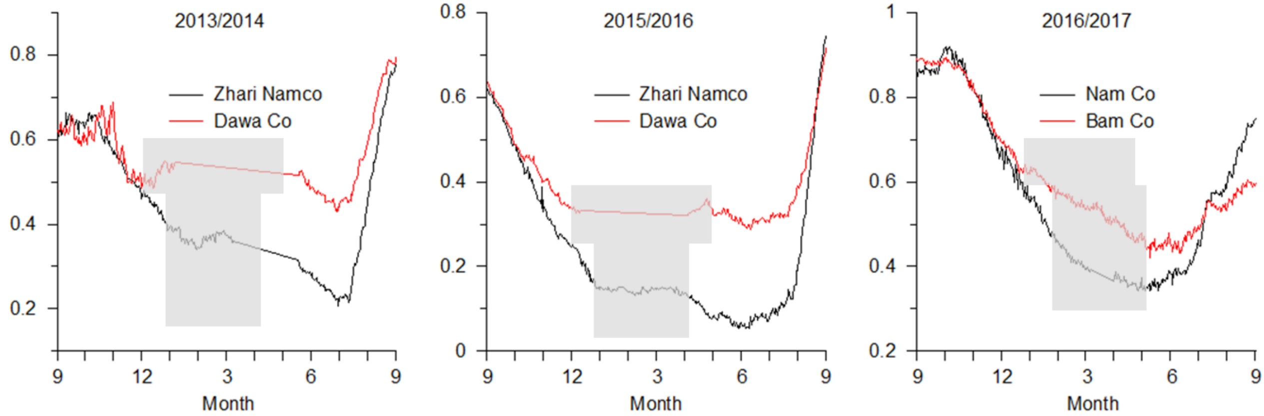

Figure 7: Different amplitude of seasonal lake level changes between deep and shallow lakes on the central TP. Relatively deep lakes: Zhari Namco (85.61 ^{o}E, 30.93 ^{o}N) and Nam Co (90.60 ^{o}E, 30.74 ^{o}N); Relatively shallow lakes: Dawa Co (84.96 ^{o}E, 31.24 ^{o}N) and Bam Co (90.58 ^{o}E, 31.26 ^{o}N). Grey rectangles represent ice covered periods at deep and shallow lakes.

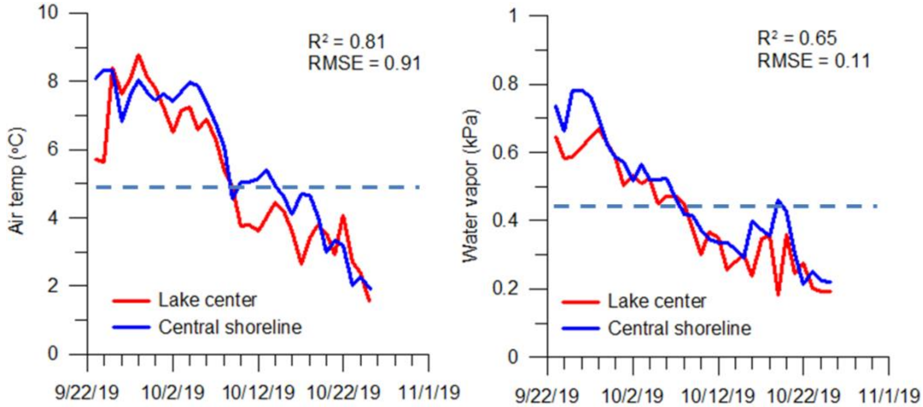

Figure 8: A comparison of air temperature and water vapour pressure between shoreline and lake centre.