Editor' comments

I have now received comments from three referees and after consulting them, I would like to ask you to consider the following issues:

1) provide precise description of used measurements (temperature and humidity), their errors and time period of averaging used for the estimation of lake evaporation,

Response: We are very grateful to the reviewers' comments. We have made detailed description about used measurement (temperature and humidity) in 'Data acquisition' part (Line 102-107). 'Two loggers were installed in an outcrop ~2 m above the lake surface. 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. The monitoring site was ventilated and therefore the meteorological condition over the lake surface can be well recorded. Air temperature and relative humidity were recorded at an interval of 1 hour and daily-averaged values were used in this study. The air temperature and humidity measurements in the shoreline were further validated by a simple AWS (GMX 600) in the Paiku Co's southern center (Section 4).'

Their uncertainties are estimated in section 3.6 (Line 363-371). 'To validate its representativeness, 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 22 September and 26 October were acquired. We made a comparison of meteorological data between shoreline and lake centre. Results show that both air temperature and relative humidity fluctuated similarly between the shoreline and lake centre (Fig. 9), 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. The RMSE of daily air temperature and water vapour pressure in the shoreline was estimated to be 0.91 ^{o}C and 0.069 kPa. The uncertainty of Bowen ratio was estimated to be 0.05 during this period by using those in the lake centre as true value, which corresponds to 5.6 W m^{-2} of latent heat flux.'

About the time period, changes in lake heat storage, sensible and latent heat fluxes and lake evaporation used in this study were calculated at weekly interval. All the other components used are daily values. We have clarified this in several places in the main text (Line 96, 106, 113, 159-160, 168-170).

2) provide (detailed) justification to estimate the above-the-lake Bowen ratio using the on-shore measurements,

Response: Air temperature, humidity and Bowen ratio using the on-shore measurements are validated by using measurement in the lake center (Fig. 9). The RMSE of daily air temperature and water vapour pressure in the shoreline was estimated to be 0.91 ^{o}C and 0.069 kPa by using those in the lake centre as true value. The uncertainty of Bowen ratio is estimated to be 0.05 during this period. We added the comparison of Bowen ratio between lake center and shoreline in Figure 9c.

3) provide estimates of error propagation to the Bowen ratio and latent/sensible and fluxes.

Response: The accuracy of Bowen ratio and heat fluxes are estimated by error propagation in the revision (section 3.6). The uncertainty of weekly Bowen ratio is estimated to be 0.05. The uncertainties of latent heat flux and lake evaporation are estimated to be 17.2 Wm^{-2} and 0.6 mm/day. The uncertainty of total lake evaporation amount is estimated to be 146 mm during ice-free period (May to Dec).

Reviewer 1#

Major comment

1) As section 3.4 with Fig. 6 would be the most important parts, in-depth explanation with discussions are expected with re-structure chapters. If you want to divide Result and Discussion, the Discussion part should contain comprehensive issues mentioned in the Result. As the 4.1 treats some kind of execution for observational accuracy, beside 4.2 compared with other lakes overlapping to 3.4, I would like to recommend, delete "4 Discussion", "5 Conclusion" may change to "5 Summary and discussion" if possible where the problems or future challenges such as 4.1 should be covered there, and 4.2 should move to Chapter. 3. (if the article HESS format accept.)

Response: We are very grateful to the constructive comments. According to your suggestions, we re-organized the structure of the paper in the revision. We have combined 'Results' and 'Discussion' sections into 'Result and discussion' (Section 3) in the revision. We believe that it would be too long if 'Conclusion' part becomes 'Summary and discussion'. More explanation about the impact of lake evaporation on seasonal lake level variations on the TP is given in Section 3.5 (Line 321-336).

2) Data and units are very important for papers based on the observational confidence, and many of them are missing. There are also uncertainties in the label and amount calculation. For instance, Fig.4, 5 are all daily value? What is the original observation interval to calculate heat/water budget? How did you filter errors/missing with correction or interpolation to born Fig. 4-6 ? In Fig.6, is this evaporation/precipitation rate? If so, they should be mm/???.

Response: Thanks for pointing out these errors. In this study, changes in lake heat storage, sensible and latent heat fluxes and lake evaporation were calculated weekly. All the other components used are daily values. For original air temperature and humidity in the shoreline and lake water temperature profile in the lake center, hourly values were monitored and daily values were used. We have clarified this in the main text (Line 96, 106, 113, 159-160, 168-170).

We have checked the unit of Fig. 4-6. The unit of lake evaporation should be mm/day. We have also addressed the units in their captions of Figures 4, 5.

3) Total river discharge was about 800-900 mm (per what??), and Av was not considered (L128). On the other hand, at L226, total evaporation for M-D was 975 mm and that is a matter of concern. They are the same order. By means of heat budget, yes that heat advection and heat needed for evaporation/condensation is quite different. But, still I can not understand the logic explaining the lake water level changes only by the evaporation term (river discharge data is missing in post-monsoon at Fig. 6b). Problem would be that there is no precise explanation about the water budget depending on the season including precipitation amount at around L125. Also, G is ignored (L128) but calculated at L151. Very strange.

Response: The unit of total river discharge was mm/year equivalent to lake level. The heat transfer between lake water and bottom sediment should be expressed as ‘G’ and changes in lake heat storage should be expressed as ‘S’. We have revised them in the revision (Line 126, 162).

Total river discharge is close to total evaporation which is about 800-1000 mm equivalent to lake level. The amount of total river discharge accounts for 2-2.5% of the total lake water storage (mean depth 42 m). In-situ observation shows that lake water temperature is 2-6 ^{o}C higher in summer than river water. We can see that the river discharge can accumulatively decrease lake water temperature by ~0.1 ^{o}C in summer, which corresponds to 2.1 W m^{-2} of heat flux between July and September and 0.07 mm/day of lake evaporation. Therefore, the impact of river discharge and precipitation on the energy budget at Paiku Co is relatively small and can be neglected. We have given a detailed description about this in the revision (Line 130-137).

4) Seasonal variation of wind speed, as shown in the reply sheet, is valuable to explain the characteristics of lake temperature stratification. Why don’t you add the wind speed variation on the Fig. 2 ?

Response: Thanks for the suggestion. We have added a comparison with the wind speed variations in Fig. S2 in the revision.

Other comments

L16 lake evaporation was “estimated” ?

Response: We have revised the sentence as ‘lake evaporation and its effects on seasonal lake level variations were investigated at Paiku Co on the southern TP based on in-situ observations of lake thermal structure and hydrometeorology (2015-2018)’.

L18 results showed ,, (results should be passed sentence)

Response: We have revised it.

L23 It is better to show lake evaporation amount for pre-monsoon, monsoon, and pos-monsoon, respectively, to emphasis their seasonality.

Response: In the revision, we have shown the amount of lake evaporation during the pre-monsoon, and pos-monsoon season as you suggest (Line 18-19).

L25 Better to unify “summer monsoon” and “monsoon”.

Response: Thanks for the suggestion. We use ‘monsoon season’ in the revision.

L27 “shallow lake” ,, again, please explain which level is shallow and which level is deep ? Also, lake depth should be added at L49,51.

Response: Shallow or deep lake in this study is not defined in this study. What we want to address is that deep lakes have larger seasonal lake level fluctuations than relatively shallow lakes due to the different heat storage and seasonal pattern of lake evaporation.

L83 Paiku Co tends to lower the lake level. So, how this evidence relates to this study's results? Better to be discussed in the last chapter.

Response: We have previously showed that the main cause of lake level decrease was mainly related to decrease in precipitation during the past decades (Lei et al., 2018). In this study, we mainly focus on the impact of lake evaporation on different amplitude of seasonal lake level changes on the TP.

L119 Just my impression that G should be ΔS and S should be G? Because, G came from Ground, and S is Storage.

Response: Thanks for the suggestion. We have revised the G and S in the revision (Line 127).

Fig. 4 Spell out SVD,LWD,LWU

Response: We have spelled out them in caption of the figure.

Please check the order of reference again.

Response: We have carefully checked the order of the references.

Reviewer 2#

(1) In Abstract (Line 16), the sentence read a little strange and the structure of the sentence should be revised.

Response: Thanks for the positive comment very much. We have revised the sentence (Line 15). ' lake evaporation at Paiku Co on the southern TP and its effect on seasonal lake level variations were investigated'.

(2) Line 21 and line 354, it should be "5 months"

Response: We have revised it.

(3) In line 134, "Ra" is not defined in the revised manuscript.

Response: Thanks for pointing out the error. 'Ra' should be 'Rl'.

(4) In line 211, I could understand that Bowen ratio is used to allocate sensible heat flux and latent heat flux following energy budget equation. But I think "Bowen ratio method" appear here is inappropriate.

Response: We agree that this sentence is inappropriate there and have deleted it in the revision.

(5) In line 303, "Runoff are shown in Tab. 3." "in" should be added.

Response: We have revised this sentence.

(6) Line 348, the sentence is suggested to be "the bottom water reached to its highest value two months later"

Response: Thanks for pointing out this error. We have revised it.

(7) In line 349, the sentence is suggested to be "The thermocline depth formed between 15 m and 25 m".

Response: We have revised this sentence in the revision, "The thermocline formed at the depth of 15~25 m".

Reviewer 3#

Main issue:

It has been the accuracy of the estimated evaporation in their study. They used on-the-shore measurements of temperature and humidity with an instrument designed for indoor use without ventilation/radiation shield (except for an instrument container box) to estimate the above-the-lake Bowen ratio. Since this is not where and how they should be measured, it is the responsibility of the authors that their measurements produce evapotranspiration with sufficient accuracy to allow them to claim their findings are meaningful against errors. My suggestion of the previous review is (1) to identify all the error sources and estimate each error magnitude, and then (2) to estimate error propagation to the Bowen ratio and latent/sensible and fluxes. Authors did (1) but did not go on to carry out (2). They do not explain why they did not in their responses (except perhaps in L284 saying "the difference of 0.6℃ .....is used to estimate the uncertainty of lake evaporation" but this estimation is not shown in the main text. Authors should respond (item-by-item) to every comment made by reviewers. If they do not agree, that is fine. But they need to explain why with supporting evidence. Please also note that some of the error estimates are for the whole year. But what is really needed is the seasonal changes of errors since they focus on seasonal changes. We need to know if the magnitude of the seasonal variation of evaporation shown by the authors is larger than the error bars. Note also that they do give their error estimate of evapotranspiration based on water balance. However, this is a rather crude estimate (see minor comment on L302-310 given below) and should be supplemented with the micrometeorological error estimates.

Response: Many thanks for the very detailed and constructive comments so many times, which are really very important for improving the manuscript. We have further revised manuscript according to these comments. Although the error estimation based on lake water balance is regarded as crude, we believe that it is a robust method, so we keep it in the revision. We further estimated the uncertainties of Bowen ratio and lake evaporation by using error propagation in the revision in section 3.6. The uncertainty of lake evaporation is estimated to be 0.6 mm/day and the total error of lake evaporation amount is 146 mm during the ice free period. From Fig. 6, we can see that the seasonal variations of lake evaporation in this study are reliable compared with its uncertainty.

We gave a more detailed description about the air temperature and humidity measurement in section 2.2 (Line 92-98). The uncertainty of air temperature and humidity in the shoreline was validated by data in the lake center in Section 3.6 (Line 365-373). 'To validate its representativeness, 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 22 September and 26 October were acquired. We made a comparison of meteorological data between shoreline and lake centre. Results show that both air temperature and relative humidity fluctuated similarly between the shoreline and lake centre (Fig. 9), 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. The RMSE of daily air temperature and water vapour pressure in the shoreline was estimated to be 0.91 ^{o}C and 0.069 kPa. The error of weekly Bowen ratio was estimated to be 0.02 during this period by using those in the lake centre as true value.'

Here we further make an estimation of seasonal changes in Bowen ratio uncertainty. According to Taylor expansion, uncertainty of Bowen ratio can be expressed as:

$$\delta B = 3.57 \times 10^{-2} \times \sqrt{\left(\frac{\Delta T_a}{T_s - T_a}\right)^2 + \left(\frac{\Delta e_a}{e_s - e_a}\right)^2}$$

Here $\delta T_a = 0.91$℃, $\delta e_a = 0.069$ kPa are used according to measurement in the center from 22 September to 26 October 2019. The results show that uncertainty of Bowen ration is 0.02 in pre-monsoon season, 0.02 in monsoon season and 0.008 in post-monsoon season. The uncertainty of seasonal latent heat flux is estimated to 2.7 W m^{-2} in pre-monsoon, 1.2 W m^{-2} in monsoon season and 1.2 W m^{-2} post monsoon season. We can see that seasonal changes in Bowen ration uncertainty and latent heat flux uncertainty are relatively small compared with their annual average. Therefore, uncertainties of Bowen ratio and evaporation during the entire ice-free period are estimated and used in this study.

Specific comments:

Title: "in the central Himalayas"; in their manuscript, they mainly explain lake evaporation and water level in the Tibetan Plateau, and not in the central Himalayas. Since not all HESS readers are familiar with the geography over there, authors should mention the relation between the two, or they should only use the Tibetan Plateau throughout the manuscript.

Response: Thanks for the suggestion. We use Tibetan Plateau throughout the manuscript instead of Himalayas in the revision.

L53-54 "The main causes ....still unclear"; aren't there any theories or hypotheses presented in previous studies? Since this will be discussed as the main point of this study in section 4.2, previously proposed ideas should be thoroughly reviewed and explained here.

Response: As far as I know, Phan et al (2012) found this phenomenon for the first time based on ICESat satellite altimetry data, but the main causes are still not investigated until now.

L56, L321 "direct measurement... energy budget method"; in my previous review, I made a comment on this saying that Bowen ratio or energy balance method is not generally considered a direct method. In the response of the authors, they simply say, "We have deleted this paragraph."(their response, L333). I take it they have agreed. Then they should revise the same point throughout their manuscript. If they do not agree, they should explain why.

Response: We agree that energy budget method is an indirect method of lake evaporation. We re-organized the sentence as 'Both the eddy covariance system and energy budget method are effective ways to determine lake evaporation (Line 55-56)'.

L63-66 "...not typically investigated through eddy covariance system because....difficult ... measurement platform"; if it is the platform issue, then the same applies to the Bowen ratio system, doesn't it?

Response: We agree that both methods have same issue. In this study, we try to avoid this issue by installing the water temperature loggers below lake ice and installing air temperature and humidity loggers in the shoreline. Although this method has its shortcoming, it is more suitable for long-term monitoring of lake evaporation.

L70 "ice-free period"; they do report evaporation and latent heat flux during the ice-covered period in Figs.5-6.

Response: Thanks for pointing out this mistake. Lake evaporation based on energy budget method during the ice-covered period may not be reliable because lake ice can significantly affect the energy balance over the lake surface. Therefore, we do not show it in Figures 7 in the revision.

L82 "highest shoreline"; is this paleo-shoreline?

Response: We have revised it.

L93 "water temperature profiles were"; add sensors after profile to write "water temperature profile sensors were".

Response: We have revised this sentence as 'Two water temperature profiles were set up in Paiku Co's southern …' (Line 92-93).

L96 "daily-averaged values"; I assume they are used only for thermal regime analysis of the lake. For the application of the energy balance method, weekly-averaged values are used, aren't they? Please clarify in the main text.

Response: We have clarified this in the main text in several places (Line 96, 106, 113, 159-160, 168-170). In this study, changes in lake heat storage, sensible and latent heat fluxes and lake evaporation were calculated at weekly interval. All the other components used are daily values.

L100 "over the lake"; this does not express the exact location of their measurement. It should be something like "above the shoreline".

Response: We have changed 'over the lake' to 'above the shoreline'.

L103 "accuracy"; mention that it is the accuracy of sensors without considering the error arising from lack of ventilation and a radiation shield.

Response: We agree that there may be some errors due to ventilation and radiation shield. We have further evaluated the accuracy of air temperature and humidity by using data from the lake center (Line 365-373).

L103 "Fig.2" this is the wrong figure number.

Response: Thanks for pointing out this error. We have deleted this figure number.

L128 "very small and can be neglected"; they make this statement based on the estimated annual lake water temperature decrease (about 0.1 ℃). However, it should be based on the estimation of seasonal impact on the storage in the energy unit. The impact should be different depending on the season (e.g., the 2-4 ℃ higher water flows into the lake from July to December), and even a small temperature change could produce a large storage change since water volume is quite large.

Response: We have further addressed this in the revision (Line 130-137). Lake water temperature was almost same to river water temperature between April and June, but 2-4^{o}C higher between July and December (Fig. S3). 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, which corresponds to 2.1 W•m-2 of heat flux error between July and September and 0.07 mm/day of evaporation uncertainty. Therefore, the influence of river discharge and precipitation on the total lake heat storage at Paiku Co is relatively small and can be neglected.

L128 "we do not consider...G"; they do consider G with Eq. (5). Perhaps this is precipitation? But then no discussion is made on the impact of rainfall advection. It should be made if G should be replaced with precipitation. If G represents "the heat transfer between the lake water and bottom sediment" (as mentioned in their response, L366-367), they still need to explain in the text why it was ignored. Note that the reason "because there is no data available" (their response, L366-367) cannot be a valid reason by itself; the reason has to be, first, scientific (and then perhaps practical).

Response: Thanks for pointing out this. In Eq. (5), G should be S (changes in lake heat storage). In fact, the heat transfer between the lake water and bottom sediment (G) is not considered. We explain it in the main text (Line 129-136) 'Meanwhile, the heat transfer between lake water and bottom sediment (G) is also neglected because groundwater discharge is usually much less than surface runoff and geothermal is not detected at the lake bottom of Paiku Co'.

L134 "Ra"; is this Rl?

Response: Thanks for pointing out this error. We have revised it in the revision.

L141-142 "the two uncertainties...... cancel each other ...daily"; I do not think this is always true, and whether or not they cancel out depends on the specific condition of the diurnal changes of wind speed, solar radiation, etc. For example, Wilson et al. (2013, doi:10.1002/jgrd.50786) and Sugita et al. (2020, doi:10.1029/2020WR027173) report the cases where daytime and nighttime values do not cancel out. I am sure some reports indicate mutual cancelation. It is condition-specific.

Response: We agree that lake water temperature at the depth of 0.4-0.8 m is different from the lake 'skin' temperature. In this study, the difference between skin temperature and bulk temperature are investigated by comparing with MODIS LST data (Line 346-355). '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 mean difference between lake surface temperature and in-situ observation is estimated to be 0.6 ^{o}C for a whole year.'

L151 Eq. (5); in this equation, the summation is from i=0 to 72.8. This should be from 0 to 13? What would you do when the water level changes? Layer number remains the same, but the representative depth of each level changes?

Response: I think it should be 72.8 because it is an integral of water depth. The maximum water depth at Paiku Co is 72.8 m. 13 layer is used in calculation. The water level changes can surely affect the depth of water temperature loggers, but it is very small relative to the large water depth. Generally, Paiku Co's lake level fluctuates in a range of 0.4-0.5 m, which is only about 1% of the mean water depth. So, we believed that the seasonal water level changes have only minor impact on the changes in lake heat storage.

L166 "reduction in wind speed (data not shown)" and L175 "significant increased wind speed.(data not shown)"; I commented on this in the previous review report. The authors' response explains that they obtained this result of "reduction" based on the Qomolangma station measurements (their response, L377-380). Then they need to explain this fact in the main text, perhaps in section 2.2 around L112. Also, they need to explain how similar the wind speeds are between the Qomolangma station and Paiku Co to make their statement valid. By the way, wind direction should also be an important factor, particularly for the estimation of measurement errors with the sensors on the shore. When wind direction is from the lake to the shoreline, this is a better situation while the opposite condition would produce a larger error.

Response: We agree that different wind directions have different representativeness of lake conditions. If we estimate hourly or daily lake evaporation, we should consider wind direction. In our case, we estimate weekly-mean evaporation error, so wind direction is not considered.

The climate of the TP is mainly dominated by the westerlies in winter, and mainly controlled by Indian summer monsoon summer. Since both the Qomolangma station and Paiku Co are located in the northern slope of the Himalayas, the climate, altitude and topography are all similar, so we believe that seasonal changes in wind speed are similar between the two places. We have added a new Figure (Figure S2) about the comparison with wind speed in the revision and given an explanation about this (Line 178-179). 'The occurrence of thermal stratification corresponded to a significant reduction in wind speed. Generally, average wind speed was relatively low between July and the middle of October, but high in other months (Fig. S2)'.

L186 "lakes on the TP are considerably lower than those in other parts of the world (Livingstone,......)"; two references are not available in the reference list, so I cannot check what "other parts of the world" means. Valid comparisons should perhaps be made between lakes in the TP with lakes of similar size and depth, and in the same latitude but in lower altitude.

Response: We checked the reference list and found that the two references are in the reference list. We selected some lakes in other parts of the world with similar area and depth, information about these lakes are given in the main text, for example area, depth and location (Line 197-208).

L187 "due to the low lake surface temperature"; please explain the logic here. I would think that when summer surface temperature is low, the temperature in a deeper layer should also become low. Therefore gradient may not be affected much by this fact.

Response: We gave further explanation about this in the main text (Line 197-208).' The vertical temperature gradients of Paiku Co and other lakes on the TP are considerably lower compared with those in other parts of the world, for example Lake Qiaodaohu (area: 580 km^2, maximum depth: 108 m) in east China (Zhang et al., 2015), Lake Zurich (area: 65 km^2, maximum depth: 136 m) on the Swiss Plateau (Livingstone, 2003) and Lake Simcoe (area: 580 km^2, maximum depth: >40 m) in Canada (Stainsby et al., 2011). This may be mainly related to the high elevation of Paiku Co. Yang et al (2010) showed that although downward shortwave radiation received by the TP is considerably higher than the surrounding lower elevation region, the downward longwave radiation is significantly lower. Due to the elevation effect, the highest air temperature at Paiku Co is only ~12 ^oC in summer. The lake surface temperature of Paiku Co (13 ^oC) is considerably lower in summer compared with lakes in other parts of the world (e.g. Lake Qiaodaohu: ~32 ^oC, Lake Zurich: ~22 ^oC and Lake Simcoe: ~22 ^oC), while the bottom water temperature (7 ^oC) does not show much difference with these lakes (e.g. Lake Qiaodaohu: ~10 ^oC, Lake Zurich: ~5 ^oC, and Lake Simcoe: ~4 ^oC)'.

L190 "3.2 Energy budget"; with this title, the sensible and latent heat fluxes should be treated here. Currently, it is in "3.3 Lake evaporation" section.

Response: We agree. In the revision, we have moved the sensible and latent heat fluxes to 'energy budget' section (section 2.2, line 230-239).

L196-198; are these numbers in the parentheses the averages during the specified period? Please indicate what it is in the main text.

Response: Yes, there numbers are the averages during the specified period. To make it easier to understand, we revised the two sentences (Line 216-219). '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, with the highest value of 212.1 W m^{-2} in June. Relatively low net radiation occurred from October to February, with the lowest value of 19.7 W m^{-2} in December.'

L222 "during the ice-free season is shown in Fig.6b"; Fig.6(a), rather than 6(b), does show evaporation during the lake ice periods.

Response: Thanks for pointing out this. We have corrected it.

L226-228 "lake evaporation ....not determined because ....covered by the lake ice..."; since it is reported in Fig.6(a), why not? The presentation has to be consistent throughout the manuscript.

Response: We believe that lake evaporation estimated during the ice covered season is not reliable because lake ice can significantly affect the energy balance over the lake surface. So the lake evaporation between January and April is not shown in the revision.

L240 "Fig. 6b,c)"; they should be 6a and 6b?

Response: Thanks for pointing out this error, we have corrected them.

L290-291 "MODIS derived lake surface temperature"; add information/reference of this product. Is this an instantaneous value? Or is it some kind of time averages? How many data points were used to derive the difference? And spatial resolution? Is it small enough to match with in-situ measurements, without the land surfaces in the field-of-view?

Response: Thanks for the suggestion. We have added some information about MODIS product (line 348-350). For MODIS Terra and Aqua land surface temperature products, two instantaneous observations were collected every day (Terra: approximately 10:30 and 22:30 local time, Aqua: approximately 13:30 and 01:30 local time). Aqua MODIS 8-day land surface temperature products (MYD11A2 V006) were used to determine the difference of lake surface temperature and bulk temperature. The product was produced with spatial resolution of about 1 km and the accuracy is estimated to be 1 K under clear sky conditions. The MODIS 8-day data is the averaged lake surface temperature of daily MODIS product over eight days (Wan Z., 2013).

Wan, Z.: Collection-6 MODIS land surface temperature products users' guide. ICESS, University of California, Santa Barbara. 2013.

L295 "whole year"; estimation should be made in shorter time intervals to allow seasonal changes of errors of the Bowen ratio/evaporation (see major comment).

Response: Please see the response to the main issue.

L302-310; is it correct that mean evaporation and mean lake level decrease were determined for May (one month) and Oct-Dec (3 months)? Is it also correct that river runoff contribution was determined once in spring and once in Autumn for three years (so the total number of measurements are 6)? Is it reasonable to compare the 6-day measurements with one- to three-month averages? Please clarify and explain them in the main text. Then why only October discharge contribution was considered? Why not the spring contribution? Is the stated contribution of 1.2 mm/d (L307) correct? A simple average would produce 1.0 mm/d. Also when you use water level, you need to consider the error magnitude of the water storage estimates (L300).

Response: For the first question, error of lake evaporation during pre-monsoon and post monsoon is estimated by comparing with lake level decrease because precipitation and runoff are already low during these periods and lake level decrease is mainly due to evaporation. So when the runoff is determined, it is reasonable to give uncertainty of lake evaporation according to lake level decrease. Runoff becomes smaller from October to December, so when the runoff in early October is determined, the largest runoff can be estimated. Therefore, we may give the largest error of lake evaporation estimation using this method.

For the second and third question, runoff was determined in early October and June every year, so we can give the largest runoff in dry seasons. Therefore, our result can give the largest error of lake evaporation estimation during the study period.

For the last three questions, the lake level decrease (1.8 mm/day) is close to lake evaporation (1.8 mm/day) in pre-monsoon season, indicating that error of lake evaporation estimation is low. In post-monsoon season, the large discrepancy has to be partly due to precipitation and runoff. We have revised the error of lake evaporation to be 144 mm during the entire ice free period.

L303 "Runoff measurements"; add an explanation on how, when, and at what intervals the measurements were made in the method section.

Response: We have added information about runoff and lake level measurements in the method section (Line 116-123). ‘As an important part of lake water budget, runoff was measured at three main rivers, Daqu, Bulaqu and Barixiongqu (Fig. 1). The water level of the three rivers was recorded automatically at 1 hour interval by using the HOBO water level logger (U20-001-01). River runoff was measured during the field expedition in spring (late May/early June) and autumn (late September/early October) using a LS1206B propeller-driven current meter (Nanjing Institute of Hydrological Automatization). Runoff was measured at least twice a day, including the largest runoff in the afternoon and lowest runoff in the morning. Meanwhile, lake level was monitored at 1 hour interval in the littoral zone of north Paiku Co (Lei et al., 2018). Daily lake level changes were used to compare with the seasonal pattern of lake evaporation in this study.’

L311 "4.2 Comparison with other lakes on the TP"; authors discuss the differences between deep and shallow lakes here. This is the issue explained in the introduction section as "unclear" so that it is good. Then how about another issue (difference of the range of seasonal lake level variation between southern and northern Tibetan Plateau) mentioned in the introduction section L45-46. Any new findings on that in this study?

Response: Thanks for the suggestion. We gave further explanation about it in the revision (Line 321-336). Our result may have further implication for the different amplitudes of seasonal lake level changes on the TP. Based on ICESat satellite altimetry data, Phan et al (2012) showed that there is larger amplitude of seasonal lake level changes on the southern TP than that on the northern TP. However, the main causes have not been investigated until now. Different seasonal patterns of lake evaporation between the southern and northern TP may partly explain this. Generally, it is much colder on the northern TP than the southern TP due to the higher elevation and latitude (Maussion et al., 2014). Lakes on the northern TP usually freeze up earlier and break up later relative to the southern TP (Kropacek et al., 2013), which results in longer ice cover duration on the northern TP (159-209 days on average) relative to the southern TP (126 days days). Longer ice cover duration on the northern TP may considerably reduce lake evaporation in post-monsoon season (Wang et al., 2020). Meanwhile, lakes on the southern TP are usually larger and deeper than those on the northern TP (e.g. Wang et al., 2009, 2010), which indicates that it can store more energy in spring and summer, and release it to the overlying atmosphere in autumn and early winter. For endorheic lakes, relatively higher lake evaporation on the southern TP in post-monsoon season may lead to larger lake level decrease compared with those on the northern TP. Therefore, the combination of the lake ice phenology and seasonal pattern of lake evaporation may lead to the different amplitudes of lake level change between the southern and northern TP. Note that other factors including lake salinity and solar radiation may also have impact on the spatial difference of lake evaporation on the TP. More studies are still needed to quantify the impact of these factors on the total precipitation amount and its seasonal distribution.

Table 1; the listed values of the accuracy of GMX600 are not accuracy but resolution. I cannot find the accuracy of "5%" in the specification of CNR4.

Response: Thanks for your detailed comments. We have revised these values in Table. 1.

Fig.6; change the unit of mm in the y-axis title to mm/month, mm/week, or mm/day.

Response: Thanks for pointing out the error. We have changed the unit of the y-axis.

Fig.7; add units to the y-axis. There are two grey rectangular shapes; add an explanation to each.

Response: We have added unit of the y-axis and added explanation of the grey rectangles.

Authors' response L348-350 "daily Bowen ratio is calculated...."; this should be explained in the main text around L145-150. As it is, the description is "all the input data were averaged at the weekly interval before lake evaporation was calculated" (L149-150), and therefore we come to believe that the Bowen ratio was calculated from weekly average temperature and humidity.

Response: In this study, daily Bowen ratio is calculated and weekly averaged Bowen ratio is used to calculate lake evaporation.

Authors' response L407 "... heat advection due to precipitation... has been mentioned in the revision"; in the main text, it simply says "the influence of ...precipitation is very small and can be neglected" (L127-128) without supporting evidence. Add evidence, please.

Response: Precipitation in the study area is about 150-200 mm, which is very small relative to large lake water depth and can only have minor impact on lake energy budget. So we do not consider its impact in this study.

Authors' response L530 "We have addressed... in Fig.8...."; I do not see it.

Response: Thanks, we have added the time period of the data used in the caption of Figure 9.

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

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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~~remain unclear on the Tibetan Plateau (TP) due to lack of comprehensive observations ~~on the Tibetan Plateau (TP)~~. In this study, lake evaporation and its effects on seasonal lake level variations ~~at Paiku Co, central Himalayas,~~ were investigated at Paiku Co on the southern TP ~~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~~. Lake evaporation at Paiku Co was estimated to be 975±146 mm during the ice-free period (May to Dec), characterized by low values of 1.7±0.6 mm/day during the pre-monsoon season (May to Jun), moderate values of 4.0±0.6 mm/day during the monsoon season (Jul to Sep) and high values of 5.5±0.6 mm/day during the post-monsoon season (Oct to Dec). There was ~5 months lag between the maximum lake evaporation (Nov) and maximum net radiation (Jun). These results indicate that the seasonal pattern of heat flux over the lake surface was significantly affected by the large lake heat storage. Contrasting hydrological and thermal intensities may play an important role in the large amplitude of seasonal lake-level variations at Paiku Co. High inflow from monsoon runoff and moderate lake evaporation, for instance, drive rapid lake-level increase during the monsoon season. In contrast, high lake evaporation and reduced inflow cause lake level to significantly decrease during the post-monsoon season. ~~While f~~For relatively 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, increased precipitation, 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 since the 1970s (~~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 (Song et al., 2014). Phan et al. (2012) showed that seasonal lake level variations on the southern TP are much larger than ~~that~~ those ~~in~~ on the northern and western TP. In-situ observations gave additional details of seasonal lake-level variations, showing that deep lakes usually exhibited considerably greater seasonal lake-level variations relative to shallow lakes (Lei et al., 2017). For example, lake levels at Zhari Namco and Nam Co, two large and deep lakes on the central TP (Wang et al., 2009, 2010), increased significantly by 0.3~0.6 m during the summer monsoon season and decreased during the post-monsoon season by a similar amount. Two nearby relatively small and shallow lakes, Dawa Co and Bam Co, exhibited considerably less lake-level variability despite showing similar seasonal cycle (Lei et al., 2017). What caused these lake systems to experience different amplitudes of seasonal lake-level variations remains unstudied. Understanding how large and small lakes respond differently to similar forcing mechanisms is critical for understanding how continued warming will impact water storage on the TP. This work additionally may provide insight into discrepancies in lake-level reconstructions from large and small lakes on the TP that are used to reconstruct and understand long-term relationships between climate and water storage.

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). Both the eddy covariance system and energy budget method are effective ways to determine lake evaporation (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~~. Meanwhile, changes in lake heat storage and its effects on lake evaporation are not quantitatively evaluated due to lack of comprehensive in-situ observations 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~~fully understand the process of lake water budget on the TP, we conducted comprehensive ~~in~~ in-situ observations at Paiku Co ~~in the central Himalayas~~on the southern TP 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 estimated ~~investigated~~ through energy budget method and its effects on seasonal lake level variations are further investigated~~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~~ analyze the seasonal pattern of lake evaporation and its impact on seasonal lake level ~~changes~~variations.

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~~on the southern TP. 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 paleo-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, lake level and runoff, 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~~set up 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~~ fluctuated 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, a~~Air temperature and ~~specific~~ relative humidity ~~over the lake~~above the shoreline 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 °C for air temperature and 2.5% ~~of~~ for 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. The monitoring site was ventilated and therefore the meteorological condition over the lake surface can be recorded. Air temperature and relative humidity were recorded at an interval of 1 hour and daily-averaged values were used in this study. ~~We admitted that I~~~~it is not the ideal location where measurements should be made, but t~~The air temperature and humidity measurements in the shoreline were ~~used as a proxy of above-lake measurements and~~further ~~validation~~ validated ~~of this proxy will be discussed~~by a simple AWS (GMX 600) in the Paiku Co's southern center (Section 2.4)~~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, daily wind speed, 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~~ in Paiku Co basin are listed in Table 1.

As an important part of lake water budget, runoff was measured at three main rivers, Daqu, Bulaqu and Barixiongqu (Fig. 1). The water level of the three rivers was recorded automatically at an interval of 1 hour by using HOBO water level loggers (U20-001-01). River runoff in spring and autumn was measured during field expedition using a LS1206B propeller-driven current meter (Nanjing Institute of Hydrological Automatization). Runoff was measured at least twice a day, including the largest runoff in the afternoon and lowest runoff in the morning. Meanwhile, lake level was monitored at an interval of 1 hour in the littoral zone of north Paiku Co (Lei et al., 2018). Daily water levels of Paiku Co and its rivers were used to compare with the seasonal pattern of lake evaporation in this study.

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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:

$$R = H + lE + SG + GS + A_v \quad (1)$$

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 S is change in lake heat storage, S G 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·m^{-2}.

Av was estimated using total river discharge and the water temperature difference between river and lake. Lake water temperature was almost samesimilar to that of river water temperature between April and June, but 2-4°C 6°C higher between July and December (data not shownFig. S3). 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 °C in a year. ThereforeIn this study, as a deep lake, the influence impact of river discharge and precipitation on the total lake heat storageenergy budget at Paiku Co is very small and therefore can be neglected. ThereforeMeanwhile, the heat transfer between lake water and bottom sediment (G) we do notis also neglected consider because groundwater discharge is usually considered to be small and the influence ofgeothermal is not detected at Paiku Co G and A_v on the lake energy budget in this study.

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

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

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$$R_l$, and R_w is the upward longwave radiation from lake. The units of the items in Eq (2) are W·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 (=5.67×10^{-8} W·m^{-2}·K^{-4}), ε_a is the water emissivity (0.97 for water surface) and T_w is lake surface temperature (°C). In this study, the water temperature at the depth of 0.4-0.8 m was used to represent the lake surface temperature. It should be noted that lake water temperature at the depth of 0.4-0.8 m does not represent 'skin' temperature. There exists surface warming during the day and surface cooling at night for high elevation lakes (Prats et al., 2018). However, the daily average between them is very similar during most time of a year because surface water can be mixed quickly by water convection or strong wind in the afternoon andThere 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 timescale.

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 (^{o}C), T_a is air temperature at 2m high above the water surface (^{o}C), 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} ^{o}C^{-1}. ~~In this study, a~~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~~ the lake water temperature at the depth of 0.4-0.8 m in the lake centre. Daily Bowen ratio is calculated in this study.

~~To match the radiation, all the input data were averaged at weekly interval before lake evaporation was calculated. Nonetheless, weekly averaged lake evaporation was calculated in order to reduce the radiation error caused by regional difference.~~

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

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

where c_w is the specific heat of water (J·kg^{-1}·K^{-1}), ρ_w is water density (=1000 kg·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~~ Changes in lake heat storage w~~as~~ere 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. Lake heat storage, sensible and latent heat fluxes and lake evaporation were calculated at interval of 7 days in order to reduce the energy budget error caused by the regional difference of solar radiation and spatial difference of lake water temperature.

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~~3). 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 vertical 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, which was generally low between July and middle October (~~data not shown~~Fig. S2)~~.~~. 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 °C between July and August, while the bottom water warmed much more slowly. As a result, the surface water temperature reached to its highest ~~temperature~~ in the late August while the bottom water temperature (>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 °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~~3). As a result, the vertical ~~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~~Fig. S2). 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 13 October ~~13th,~~ 2016, and to 70 m water depth about two weeks later (30 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 °C from July to October, but increased abruptly from 6.9 to 8.6 °C in less than one week (~~October~~ 25~~th~~~~–~~ October to 30 October~~th~~). 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~~3~~, Fig., 3~~4). Water temperature of the whole lake decreased gradually from 8.6 to 1 °C from November to January and remained stable at 1-2 °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~~ vertical temperature gradients at Paiku Co and other lakes on the TP are considerably lower ~~than~~ compared with those in other parts of the world, for example Lake Qiaodaohu (area: 580 km^2, maximum depth: 108 m) in east China (~~Livingstone, 2003; Stainsby et al., 2011,~~ Zhang et al., ~~2015~~2014), Lake Zurich (area: 65 km^2, maximum depth: 136 m) on the Swiss Plateau (Livingstone, 2003) and Lake Simcoe (area: 580 km^2, maximum depth: >40 m) in Canada (Stainsby et al., 2011)~~,~~. ~~which~~ This may be mainly ~~is probably due to~~ related to the high elevation of Paiku Co. Yang et al (2010) showed that although downward shortwave radiation received by the TP is considerable higher than its surrounding area, the downward longwave radiation is significantly lower. ~~low lake surface temperature in summer in this high elevation area.~~ Due to the elevation effect, the highest air temperature at Paiku Co is only ~12 °C in summer. The highest lake surface temperature at Paiku Co (~13 °C) is also much lower than that those in other parts of the world, e.g., Lake Qiaodaohu (~32 °C), Lake Zurich (~22 °C) and Lake Simcoe (~22 °C).

>>Fig. ~~2~~3<<

>>Fig. ~~3~~4<<

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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~~5), 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 of 212.1 W·m^{-2} 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 of 19.7 W·m^{-2} in December~~ (19.7 W·m^{-2})~~.

>>Fig. ~~4~~5<<

Changes in lake heat storage at Paiku Co were quantified using in-situ observations of water temperature profile and detailed lake bathymetry (Fig. ~~4e~~5e), 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.

The Bowen ratio varied in a range of -0.26~+0.37 (Fig. ~~5~~6c). 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~~6<<

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~~7a. Lake evaporation was generally low in pre-monsoon season (May and June) with an average value of 1.7±0.6 mm/day. In monsoon season (July ~~and August~~to September), lake evaporation increased rapidly from 2.9±0.7 to ~~4~~5.1±0.6 mm/day. High lake evaporation occurred in post monsoon season ~~between (September~~October ~~and~~ to December), with an average value of 5.4 mm/day. The total lake evaporation was estimated to be 975±146 mm during ice-free period 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 this~~is ~~e study period~~.

>>Fig. ~~6~~7<<

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).

~~4 Discussion~~

3.44.13.4 ComparisonImpact of lake heat storage on lake evaporation with other lakes on the TP

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, Z. Li 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, X. Li 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.

3.4 54.23.5 Implications for the different amplitude of seasonal lake-level variations across 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.

Fig.~~6a~~ 7 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~~7a~~, c~~b), 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.

The seasonal pattern of lake evaporation at Paiku Co can also be reflected by lake-level changes during the pre-monsoon and post-monsoon seasons. During the post-monsoon season, Paiku Co's lake level decreased considerably at a rate of 3.8 mm/day on average, which is in contrast to the slight decreasing rate of 1.3 mm/day during the pre-monsoon season (Fig. 7c). Lake level decrease during these periods is mainly related to lake evaporation because the surface runoff had still a weak impact on lake-level changes during the two dry seasons (Tab. 3). 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 the slight lake-level decrease.

On a broader scale, 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~~8), 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~~8<<

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The seasonal pattern of lake evaporation may also have significant impact on the different seasonal lake-level variations across the TP. Based on ICESat satellite altimetry data, Phan et al (2012) showed that there was a larger amplitude of seasonal lake-level variations on the southern TP relative to the northern TP. However, the main causes have not been investigated until now. Generally, it is much colder on the northern TP than the southern TP due to the higher elevation and latitude (Maussion et al., 2014). Lakes on the northern TP usually freeze up earlier and break up later relative to the southern TP (Kropacek et al., 2013), which results in longer ice cover duration on the northern TP (159-209 days on average) relative to the southern TP (126 days days). Longer ice cover duration on the northern TP can considerably reduce lake evaporation during the post-monsoon season (Wang et al., 2020). Meanwhile, lakes on the southern TP are usually larger and deeper than those on the northern TP (e.g. Wang et al., 2009, 2010), which indicates that it can store more energy in spring and summer, and release it to the overlying atmosphere in autumn and early winter. For endorheic lakes, relatively higher lake evaporation in post-monsoon season may lead to larger lake-level decrease on the southern TP compared with those on the northern TP. Therefore, the combination of the lake ice phenology and seasonal pattern of lake evaporation may lead to the different amplitudes of lake-level variations between the southern and northern TP. Note that other factors including lake salinity and solar radiation may also have impact on the spatial difference of lake evaporation on the TP. More studies are still needed to quantify the impact of these factors on the total precipitation amount and its seasonal distribution.

3.6 Uncertainty of lake evaporation

Uncertainty of lake evaporation can be mainly caused by the uncertainties of the following factors: solar radiation, lake surface temperature, changes in lake heat storage and meteorological data (air temperature and humidity).

Firstly, solar radiation and atmospheric longwave radiation at Qomolangma station were used to represent those 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). The results show that daily solar radiation at the two sites exhibited similar seasonal fluctuations (R^2=0.55, P<0.001). The uncertainty of weekly solar radiation was estimated to be 3.4 W·m^{-2} (ΔE_1). The uncertainty in the atmospheric longwave radiation is not estimated, but the variations of solar radiation and atmospheric longwave radiation are usually opposite at a site, so their total uncertainty should not exceed the individual uncertainty.

Secondly, lake water temperature at the depth of 0.4-0.8 m, not lake skin temperature is used to calculate upward longwave radiation. 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 8-day lake surface temperature product is used to determine the difference between lake bulk temperature and skin temperature. The product is produced with spatial resolution of about 1 km and the accuracy is estimated to be 1 K under clear sky conditions (Wan, 2013). 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 mean difference between lake surface temperature and in-situ observation is estimated to be 0.6

°C for a whole year. The uncertainty of upward longwave radiation is estimated to be 12.2 W·m^{-2} (ΔE_2) according to this mean temperature difference.

Thirdly, uncertainty of changes in lake heat storage mainly comes from the spatial distribution of lake water temperature. Spatial difference of lake water temperature between Paiku Co's southern and northern basins in 2016/2017 was compared in Fig. S4. Since the northern basin is much deeper than the southern basin, lake water in the northern basin warmed more slowly than that in the southern basin during the spring and early summer, and cooled more slowly during the autumn and early winter. The daily surface water temperature in the southern basin was about 0.85 °C higher on average than that in the northern basin between April and September, but was about 0.45 °C lower on average in November and December (Fig. S3). Water temperature became spatially uniform at both basins between January and March. Similar spatial difference can also be found at 10 m depth, indicating that this phenomenon may exist in the whole epilimnion. The uncertainty of changes in lake heat storage is estimated to be 10.2 W·m^{-2} (ΔE_3).

Fourthly, air temperature and relative humidity at the shoreline are used to calculate Bowen ratio and lake evaporation. To validate its representativeness, 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 22 September and 26 October were acquired. We made a comparison of meteorological data between shoreline and lake centre. Results show that both air temperature and relative humidity fluctuated similarly between the shoreline and lake centre (Fig. 9), 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. The RMSE of daily air temperature and water vapour pressure in the shoreline was estimated to be 0.91 °C and 0.069 kPa. The uncertainty of Bowen ratio was estimated to be 0.02 during the ice-free period by using those difference between the lake centre and shoreline, which corresponds to 2.2 W·m^{-2} of heat flux (ΔE_4).

>>Fig. 9<<

By using error propagation, the uncertainties of latent heat flux and lake evaporation are estimated to be 17.2 Wm^{-2} (=$\sqrt{\Delta E_1{}^2 + \Delta E_2{}^2 + \Delta E_3{}^2 + \Delta E_4{}^2}$) and 0.6 mm/day. The uncertainty of total lake evaporation amount is estimated to be 146 mm during the ice-free period (May to Dec).

Uncertainty of total lake evaporation is also estimated by comparing lake-level changes during the pre-monsoon and post-monsoon seasons. Runoff measurements at the three largest rivers feeding Paiku Co are shown in 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 1.0 mm/day on average in October, thereby partially offsetting lake-level changes from lake evaporation. This difference (0.6 mm/day) between the estimated lake evaporation and the in-situ measurements of lake-level decrease and runoff during the post-monsoon season is very close to the uncertainty of lake evaporation estimated by error propagation.

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 (R2=0.55, P<0.001), with RMSE of 23.9 W 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 oC 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 oC 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 oC higher than lake body temperature. Therefore, the difference between lake surface temperature and in-situ observation is estimated to be 0.6 oC 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

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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 km2; 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 km2; 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

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~~~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~~ 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 later (middle to late Oct.). The thermocline formed at the depth of ~~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~~ 168 mm between May and December, with low values between May and June (1.7 ±0.7 mm/day), and high values between October and December (5.4 ±0.7 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

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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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References

Blanken, P. D., Rouse, W. R., Culf, A.D., Spence, C., Boudreau, L.D., Jasper, J.N., Kochtubajda, B., Schertzer, W. M., Marsh, P., and Verseghy, D.: Eddy covariance measurements of evaporation from Great Slave Lake, Northwest Territories, Canada, Water Resour. Res., 36, 1069–1078, 2000.

Cai, Y., Ke, C. Q., and Duan, Z.: Monitoring ice variations in Qinghai Lake from 1979 to 2016 using passive microwave remote sensing data. Sci. Total Environ., 607–608, 120-131, doi:425 10.1016/j.scitotenv.2017.07.027, 2017.

Dai, Y., Gao, Y., Zhang, G., and Xiang, Y.: Water volume change of the Paiku Co in the southern Tibetan Plateau and its response to climate change in 2003–2011, J. Glaciol. Geocryol., 35 (3), 723–732, 2013.

Maussion, F., Scherer, D., Mölg, T., Collier, E., Curio, J., and Finkelnburg, R.: Precipitation Seasonality and Variability over the Tibetan Plateau as Resolved by the High Asia Reanalysis, J. Climate, 27, 1910–1927, 2014.

Guo, Y., Zhang, Y., Ma, N., Song, H., Gao, H.: Quantifying Surface Energy Fluxes and Evaporation over a significant Expanding Endorheic Lake in the Central Tibetan Plateau, J. Meteorol. Soc. Jpn., 94, 453–465, 2016.

Gianniou, S. K., and Antonopoulos V. Z.: Evaporation and energy budget in Lake Vegoritis. Greece, J. Hydrol., 345, 212–223, 2007.

Haginoya, S., Fujii H., Kuwagata T., Xu J., Ishigooka Y., Kang S., and Zhang Y.: Air-lake interaction features found in heat and water exchanges over Nam Co on the Tibetan Plateau, Sci. Online Lett. Atmos., 5, 172–175, doi:10.2151/sola.2009-044, 2009.

Henderson-Sellers, B. Engineering Limnology. Pitman Publishing, Great Britain. 1984.

Huang, W., Cheng, B., Zhang, J., Zhang, Z., Vihma, T., Li, Z., Niu, F.: Modeling experiments on seasonal lake ice mass and energy balance in the Qinghai-Tibet Plateau: a case study, Hydrol. Earth Syst. Sci. 23, 2173–3186, 2019.

Ke, C., Tao, A., Jin, X.: Variability in the ice phenology of Nam Co Lake in central Tibet from scanning multichannel microwave radiometer and special sensor microwave/imager: 1978 to 2013. J. Appl. Remote. Sens. 7, 073477. http://dx.doi.org/10. 1117/1.JRS.7.073477, 2013.

Kropacek, J., Maussion, F., Chen, F., Hoerz, S., Hochschild, V.: Analysis of ice phenology of lakes on the Tibetan Plateau from MODIS data. Cryosphere, 7 (1), 287–301. http://dx.doi.org/10.5194/tc-7-287-2013, 2013.

Lazhu, Yang, K., Wang, J., Lei, Y., Chen, Y., Zhu, L., Ding, B., and Qin, J.: Quantifying evaporation and its decadal change for Lake Nam Co, central Tibetan Plateau, J. Geophys. Res. Atmos., 121, doi:10.1002/2015JD024523, 2016.

Letu, H., Yang, K., Nakajima, T.Y., Ishimoto, H., Nagao, T.M., Riedi, J., Baran, A.J., Ma, R., Wang, T., Shang, H., Khatri, P., Chen, L., Shi, C., Shi, J.: High-resolution retrieval of cloud microphysical properties and surface solar radiation using Himawari-8/AHI next-generation geostationary satellite. Remote Sens. Environ., 239, 111583, doi:10.1016/j.rse.2019.111583, 2020.

Lei, Y., Yao, T., Bird, B.W., Yang, K., Zhai, J., and Sheng, Y.: Coherent lake growth on the central Tibetan Plateau since the 1970s: Characterization and attribution, J. Hydrol., 483, 61–67, 2013.

Lei, Y., Yang, K., Wang, B., Sheng, Y., Bird, B., Zhang, G., and Tian, L.: Response of inland lake dynamics over the 405 Tibetan Plateau to climate change, Clim. Change, 125, 281–290, 2014.

Lei, Y., Yao, T., Yang, K., Sheng, Y., Kleinherenbrink, M., Yi, S., Bird, B.W., Zhang, X., Lazhu, Zhang, G.Q.: Lake seasonality across the Tibetan Plateau and their varying relationship with regional mass changes and local hydrology, Geophys. Res. Lett., 44, doi:10.1002/2016GL072062, 2017.

带格式的: 字体：(中文) +中文正文 (宋体), (中文) 中文(中国)

Lei Y., and Yang K.: The cause of rapid lake expansion in the Tibetan Plateau: climate wetting or warming? WIREs Water, e1236. DOI:10.1002/wat2.1236, 2017.

Lei, Y., Yao, T., Yang, K., Bird B.W., Tian, L., Zhang, X., Wang W., Xiang Y., Dai, Y.F., Lazhu, Zhou, J., Wang, L.: An integrated investigation of lake storage and water level changes in the Paiku Co basin, central Himalayas, J. Hydrol., 562, 599–608, doi.org/10.1016/j.jhydrol.2018.05.040, 2018.

Lenters, J., Kratz, T., and Bowser, C.: Effects of climate variability on lake evaporation: results from a long-term energy budget study of Sparkling Lake, northern Wisconsin (USA), J. Hydrol., 308, 168–195, 2005.

~~Li, Z., Lyu, S., Ao, Y., Wen, L., Zhao, L., and Wang S.: Long-term energy flux and radiation balance observations over Lake Ngoring, Tibetan Plateau. Atmos. Res., 155, 13–25, doi:10.1016/j.atmosres.2014.11.019, 2015.~~

Li, W., Li, S., and Pu P.: Estimates of plateau lake evaporation: A case study of Zige Tangco, J. Lake Sci., 13(3): 227–232, 2001.

Li, X.Y., Ma Y.J., Huang Y.M., Hu X., Wu X.C., Wang P., Li G.Y., and Zhang S.Y.: Evaporation and surface energy budget over the largest high-altitude saline lake on the Qinghai-Tibet Plateau, J. Geophys. Res.Atmos., 121, 10,470–10,485, doi:10.1002/2016JD025027, 2016.

Li, Z., Lyu, S., Ao, Y., Wen, L., Zhao, L., and Wang S.: Long-term energy flux and radiation balance observations over Lake Ngoring, Tibetan Plateau. Atmos. Res., 155, 13–25, doi:10.1016/j.atmosres.2014.11.019, 2015.

~~Li, W., Li, S., and Pu P.: Estimates of plateau lake evaporation: A case study of Zige Tangco, J. Lake Sci., 13(3): 227–232, 2001.~~

Livingstone, D.: Impact of secular climate change on the thermal structure of a large temperate central European lake. Climatic Changes, 57, 205-225, 2003

Luo, J., Niu, F., Lin, Z., Liu, M., Yin, G. Thermokarst lake changes between 1969 and 2010 in the Beilu River Basin, Qinghai–Tibet Plateau, China. Sci. Bull. 60(5),556–564, 2015.

Ma, N., J. Szilagyi, Niu, G.Y., Zhang, Y., Zhang, T., Wang, B., and Wu, Y.: Evaporation variability of Nam Co Lake in the Tibetan Plateau and its role in recent rapid lake expansion, J. Hydrol., 537, 27–35, doi:10.1016/j.jhydrol.2016.03.030, 2016.

Ma, R., Yang, G., Duan, H., Jiang, J., Wang, S., Feng, X., Li, A., Kong, F., Xue, B., Wu, J., Li, S.: China's lakes at present: number, area and spatial distribution. Sci. China Earth Sci. 54(2), 283–289, 2011.

Morrill, C.: The influence of Asian summer monsoon variability on the water balance of a Tibetan lake, J. Paleolimnol., 32, 273-286, 2004.

Nie, Y., Zhang, Y., Ding, M., Liu, L., Wang, Z.: Lake change and its implication in the vicinity of Mt. Qomolangma (Everest), central high Himalayas, 1970–2009, Environ. Earth Sci. 68, 251–265, 2013.

Pan, X., Yu, Q., You, Y., Chun, K.P., Shi, X., Li, Y.: Contribution of supra-permafrost discharge to thermokarst lake water balances on the northeastern Qinghai-Tibet Plateau, J. Hydrol., 555, 621–630, 2017.

Phan, V. H., Lindenbergh, R., and Menenti, M.: ICESat derived elevation changes of Tibetan lakes between 2003 and 2009, Int. J. Appl. Earth Obs., 17, 12–22, 2012.

Prats, J., Reynaud, N,, Rebière, D., Peroux, T., Tormos, T., and Danis, P.A.: LakeSST: Lake Skin Surface Temperature in French inland water bodies for 1999-2016 from Landsat archives. Earth Syst. Sci. Data, 10, 727–743, 2018.

Phan, V. H., Lindenbergh, R., and Menenti, M.: ICESat derived elevation changes of Tibetan lakes between 2003 and 2009, Int. J. Appl. Earth Obs., 17, 12–22, 2012.

Qiao, B., Zhu, L., Wang, J., Ju, J., Ma, Q., Huang, L., Chen, H,, Liu, C., Xu, T.: Estimation of lake water storage and changes based on bathymetric data and altimetry data and the association with climate change in the central Tibetan Plateau, J. Hydrol., 578, 124052, 2019.

Rosenberry, D.O., Winter, T.C., Buso, D.C., and Likens, G. E.: Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA, J. Hydrol., 340, 149–166, doi:10.1016/j.jhydrol.2007.03.018, 2007.

Rouse, W. R., Oswald, C. J., Binyamin, J., Blanken, P. D., Schertzer, W. M., and Spence, C.: Interannual and seasonal variability of the surface energy balance and temperature of central Great Slave Lake, J. Hydrometeor., 4, 720–730, 2003.

Rouse, W. R., Blanken, P. D., Bussières, N., Oswald, C.J., Schertzer, W.M., Spence, C., and Walker, A.E.: An Investigation of the Thermal and Energy Balance Regimes of Great Slave and Great Bear Lakes, J. Hydrometeor., 9, 1318–1333., 2008.

Stainsby, E.A., Winter J.G., Jarjanazi, H., Paterson, A.M., Evans, D.O., Young, J.D.: Changes in the thermal stability of Lake Simcoe from 1980 to 2008. J. Great Lakes Res., 37, 55–62, 2011.

Song, C., Huang, B., Ke, L., and Richards K.: Seasonal and abrupt changes in the water level of closed lakes on the Tibetan Plateau and implications for climate impacts, J. Hydrol., 514, 131–144, 2014.

Su, D., Hu, X., Wen, L., Lyu, S., Gao, X., Zhao, L., Li, Z., Du, J., and Kirillin G.: Numerical study on the response of the largest lake in China to climate change. Hydrol. Earth Syst. Sci., 23, 2093–2109, https://doi.org/10.5194/hess-23-2093-2019, 2019.

Sugita, M.: Spatial variability of the surface energy balance of Lake Kasumigaura and implications for flux measurements, Hydrological Sci. J., DOI:10.1080/02626667.2019.1701676, 2019.

Rosenberry, D.O., Winter, T.C., Buso, D.C., and Likens, G. E.: Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA, J. Hydrol., 340, 149–166, doi:10.1016/j.jhydrol.2007.03.018, 2007.

Stainsby, E.A., Winter J.G., Jarjanazi, H., Paterson, A.M., Evans, D.O., Young, J.D.: Changes in the thermal stability of Lake Simcoe from 1980 to 2008. J. Great Lakes Res., 37, 55–62, 2011

Tang, W., Li, J., Yang, K., Qin, J., Zhang, G., Wang, Y.: Dependence of remote sensing accuracy of global horizontal irradiance at different scales on satellite sampling frequency. Solar Energy, 193, 597-603, 2019.

Wang, B., Ma, Y., Ma, W., and Su, Z.: Physical controls on half-hourly, daily, and monthly turbulent flux and energy budget over a high-altitude small lake on the Tibetan Plateau, J. Geophys. Res. Atmos., 122, 2289–2303, doi:10.1002/2016JD026109, 2017.

带格式的: 字体:(中文) +中文正文 (宋体), (中文) 中文(中国)

Wang, B., Ma, Y., Wang, Y., Su, Z., Ma, W.: Significant differences exist in lake-atmosphere interactions and the evaporation rates of high-elevation small and large lakes, J. Hydrol., 573, 220–234, 2019.

Wang, B., Ma, Y., Su, Z., Wang, Y., Ma, W.: Quantifying the evaporation amounts of 75 high-elevation large dimictic lakes on the Tibetan Plateau. Sci. Adv. 6, eaay8558, 2020.

Wang, J., Zhu, L., Daut, G., Ju, J., Lin, X., Wang, Y., and Zhen, X.: Investigation of bathymetry and water quality of Lake Nam Co, the largest lake on the central Tibetan Plateau, China, Limnology, 10, 149–158, doi:10.1007/s10201-009-0266-8. 2009.

Wang, J., Peng, P., Ma, Q., Zhu, L.: Modern limnological features of Tangra Yumco and Zhari Namco, Tibetan Plateau, J. Lake Sci., 22 (4), 629–632, 2010.

Wang, J., Huang, L., Ju, J., Daut, G., Wang, Y., Ma, Q., Zhu, L., Haberzettl, T., Baade, J., Mäusbacher, R.: Spatial and temporal variations in water temperature in a high-altitude deep dimictic mountain lake (Nam Co), central Tibetan Plateau. J. Great Lakes Res. 45, 212–223, 2019.

Wang, M., Hou, J., Lei, Y.: Classification of Tibetan lakes based on variations in seasonal lake water temperature. Chin, Sci. Bull., DOI 10.1007/s11434-014-0588-8, 2014.

Wang, Y., Yang, K., Zhou, X., Wang, B., Chen, D., Lu, H., Lin, C., and Zhang, F.: The formation of a dry - belt in the north side of central Himalaya Mountains. Geophys. Res. Lett., 46, 2993–3000. https://doi.org/10.1029/2018GL081061, 2019.

Wetzel, R.G.: Limnology: lake and river ecosystems. Elsevier, San Diego, 2001.

Winter, T., Buso, D., Rosenberry, D., Likens, G., Sturrock Jr., A., Mau, D.: Evaporation determined by the energy-budget method for Mirror Lake, New Hampshire, Limnol. Oceanogr. 48 (3), 995–1009, 2003.

Wünnemann, B., Yan, D., Ci, R.: Morphodynamics and lake level variations at Paiku Co, southern Tibetan Plateau, China, Geomorphology. 246: 489–501, 2015.

Xu, J., Yu, S., Liu, J., Haginoya, S., Ishigooka, Y., Kuwagata, T., Hara, M., and Yasunari T.: The implication of heat and water balance changes in a lake basin on the Tibetan Plateau. Hydrol. Res. Lett., 3, 1–5, 2009.

Yang, K., He, J., Tang, W., Qin, J., and Cheng, C.: On downward shortwave and longwave radiations over high altitude regions: Observation and modeling in the Tibetan Plateau, Agric. For. Meteorol., 150(1), 38-46, doi:10.1016/j.agrformet.2009.08.004, 2010

Yu, S., Liu, J., Xu, J., and Wang, H.: Evaporation and energy balance estimates over a large inland lake in the Tibet-Himalaya, Environ. Earth Sci., 64(4), 1169–1176, 2011.

Zhang, G., Yao, T., Xie, H., Zhang, K., Zhu, F.: Lakes' state and abundance across the Tibetan Plateau, Chin. Sci. Bull. 59 (24), 3010–3021, 2014a.

Zhang, G., Yao, T., Xie, H., Qin, J., Ye, Q., Dai, Y., & Guo, R.: Estimating surface temperature changes of lakes in the Tibetan Plateau using MODIS LST data. Journal of Geophysical Research: Atmospheres, 119, 8552–8567. https://doi.org/10.1002/2014JD021615, 2014b.

Zhang, Q., and Liu, H.: Seasonal changes in physical processes controlling evaporation over inland water, J. Geophys. Res. Atmos., 119, 9779–9792, doi:10.1002/2014JD021797, 2014.

Zhang, Y., Wu, Z., Liu, M., He, J., Shi, K., Wang, M., and Yu, Z.: Thermal structure and response to long-term climatic changes in Lake Qiandaohu, a deep subtropical reservoir in China, Limnol. Oceanogr., 59(4), 1193–1202, 2014.

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~~3 °C ~~1~~2%	South center	2019.9-2019.10
R_s and R_l	Kipp & Zonen CNR4 net radiometer	~~5~~1%	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 ($W \cdot m^{-2}$)			Heat storage ($W \cdot m^{-2}$)			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.

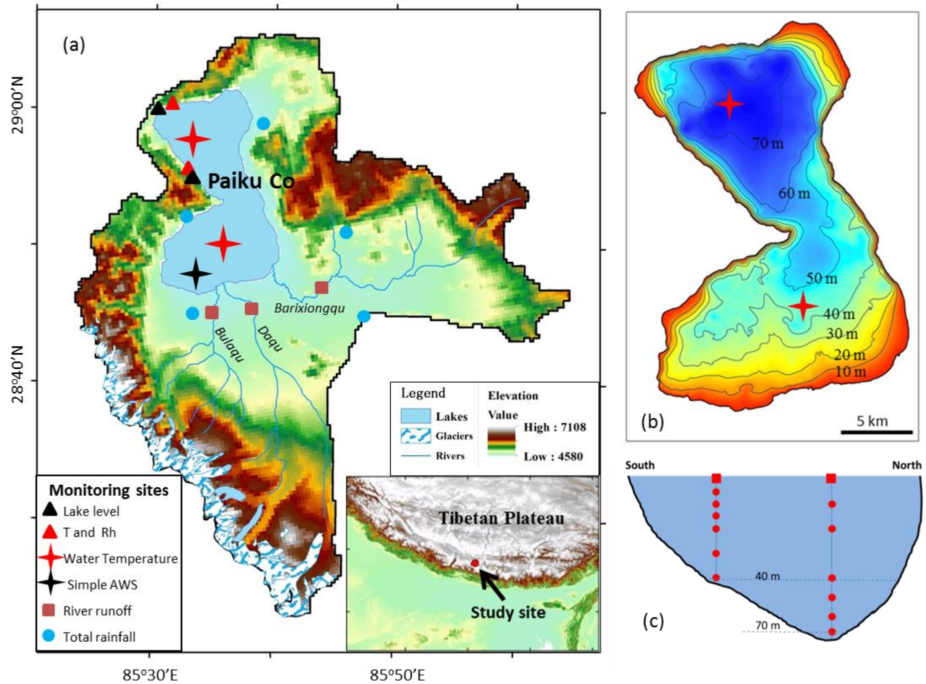

Figure 1: Monitoring sites of lake water budget at Paiku Co basin. (a): Monitoring sites of lake level, hydro-meteorology, water temperature profile, runoff, and total rainfall. (b): The isobath of Paiku Co and the two monitoring sites of water temperature profile. (c): The water temperature monitoring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

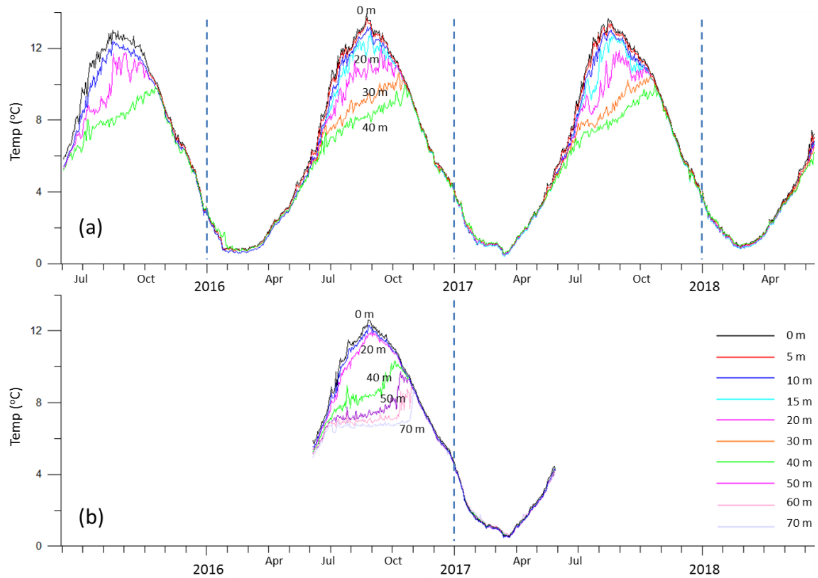

Figure 22: Time series of daily lake water temperature at different water depths in Paiku Co's southern (a) and northern (b) basins.

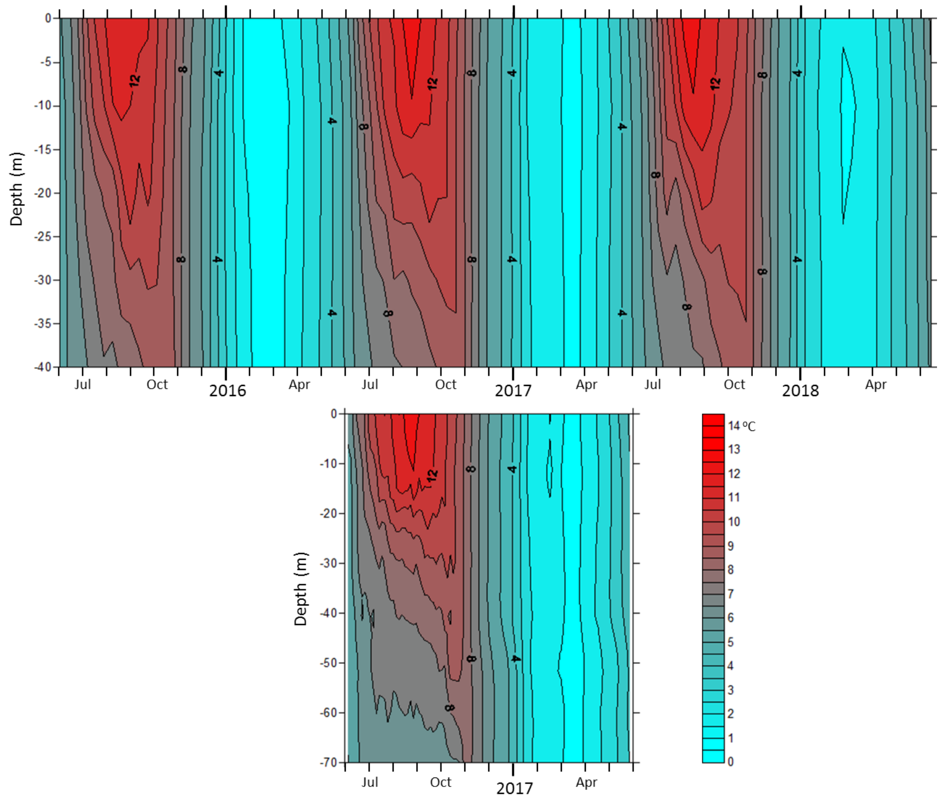

Figure ~~3~~3: Depth-time diagram of isotherm (°C) in Paiku Co's southern (upper, 42 m in depth) and northern (below, 72 m in depth) basins between June 2015 and May 2018.

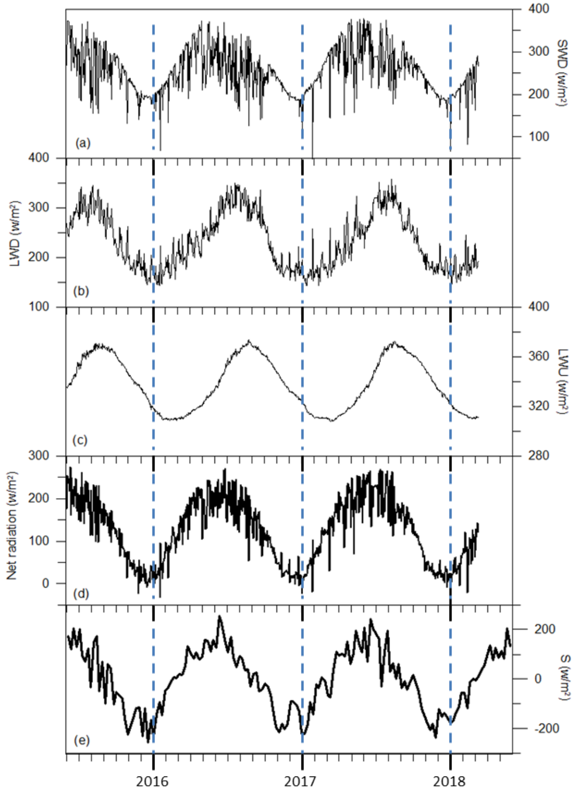

Figure 4: The main components of energy budget at the lake surface and changes in lake heat storage. (a): <u>Daily</u> ~~D~~<u>d</u>ownward short wave radiation, (b): <u>Daily</u> ~~A~~<u>a</u>tmospheric long wave radiation to lake, (c): <u>Daily</u> ~~L~~<u>l</u>ong wave radiation emitted from lake, (d): <u>Daily</u> ~~N~~<u>n</u>et radiation, (e): Weekly <u>averaged</u> changes in lake heat storage (~~G~~<u>S</u>).

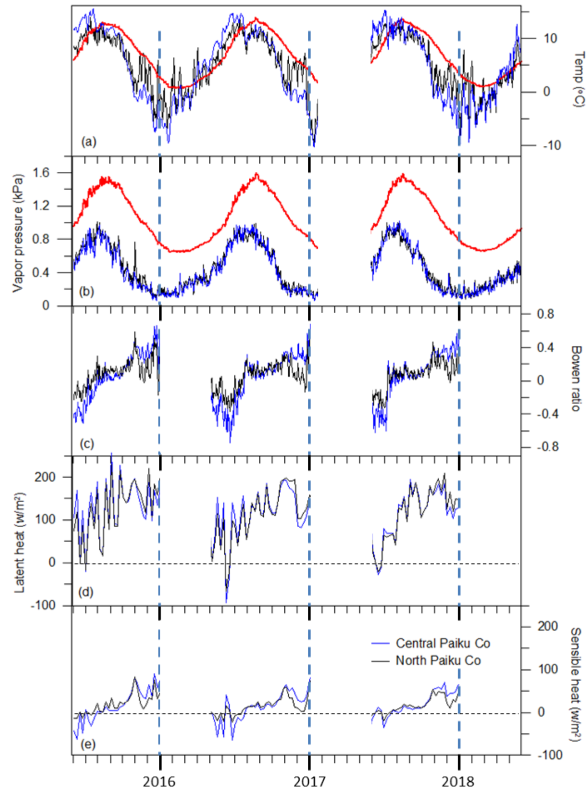

Figure 5: Hydrometeorology and heat flux at the lake surface. (a): Daily Air air temperature and daily surface water temperature (red line), (b): Daily Aactual vapour pressure at lake surface (red line) and the overlying atmosphere, (c): Daily BBowen ratio, (d-e): Weekly averaged latent and sensible heat fluxes 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.

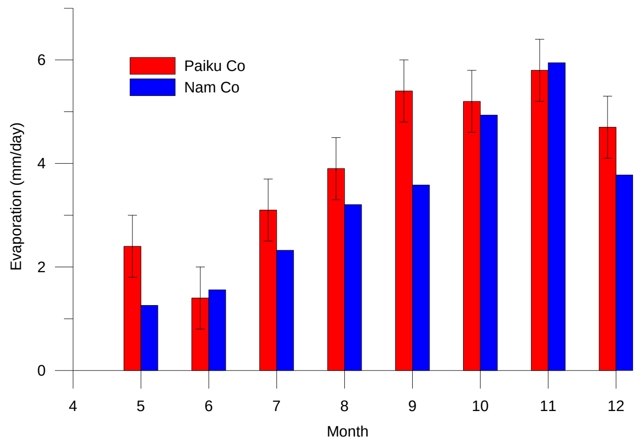

Fig. 6 A comparison of monthly lake evaporation between Paiku Co and Nam Co on the central TP. Lake evaporation at Nam Co was determined by using eddy covariance system in the lake center (Wang et al., 2019). The bars denote the uncertainty of lake evaporation at Paiku Co.

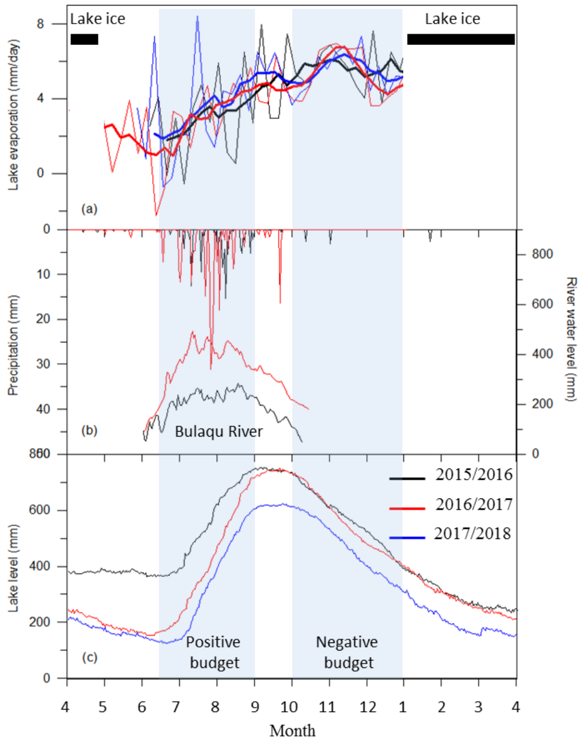

Figure ~~6~~7: The main components of lake water budget at Paiku Co. (a): Lake evaporation (mm/day) derived from the north shoreline of Paiku Co. (b): Daily ~~P~~precipitation (mm) at Qomolangma station and water level (mm~~/day~~) of Bulaqu River in 2015 and 2016. Note the Y axis (left) of precipitation is reversed. (c): Daily lake level variations (mm) 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.

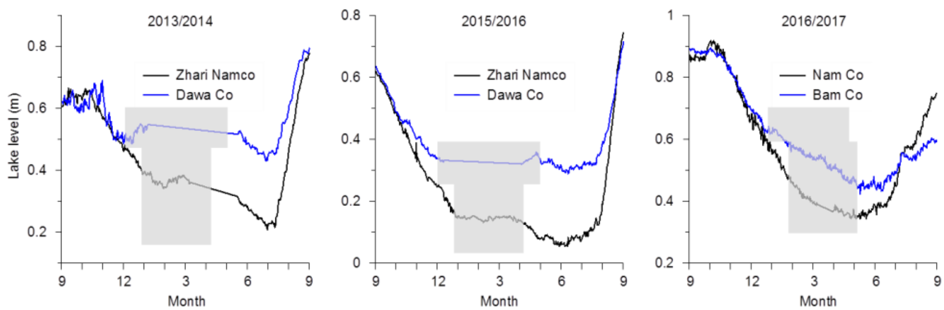

Figure ~~7~~8: Different amplitude of seasonal lake level changes between deep and shallow lakes on the central TP. Relatively deep lakes: Zhari Namco (85.61 °E, 30.93 °N) and Nam Co (90.60 °E, 30.74 °N); Relatively shallow lakes: Dawa Co (84.96 °E, 31.24 °N) and Bam Co (90.58 °E, 31.26 °N). Grey rectangles in each figure represent ~~different~~ lake ice ~~covered~~ phenology periods at ~~relatively deep and shallow~~ the two lakes.

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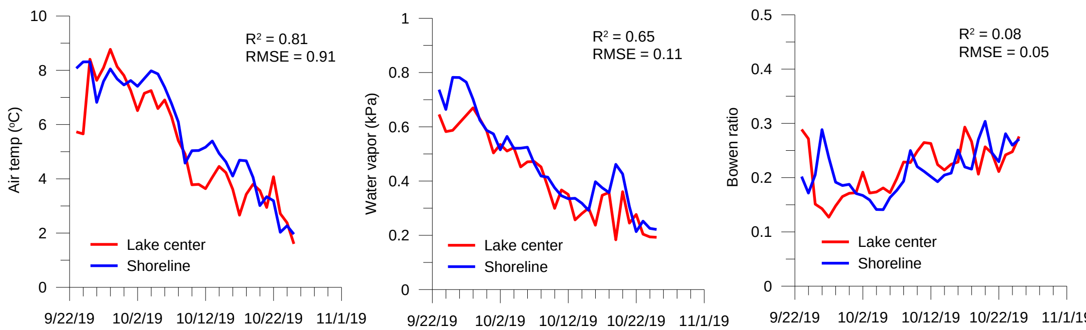

1365 **Figure 9: A comparison of air temperature, water vapour pressure and Bowen ratio between central shoreline and lake centre.**