Response to reviewer #1

This paper reported the seasonal changes of lake water profile, lake levels, surface heat budget, and evaporations by three years in-situ observation data. They showed very interesting characteristics representing lake environment in southern edge of the TP, that gives us the hints to understand basic processes of heat/water budget of mountain lakes under Indian monsoon climate. As authors introduced in the introduction, lakes on the TP are changing. It is very important to reveal that how the global environment change could modify the lake environment through land-atmosphere interaction. The contents showed basic timelines of observed data with estimated heat budget and evaporation amount, and natures could be easily captured by figures.

Response: We are very grateful to these comments and we believe that these comments are very helpful to improve the paper. We have revised the paper according to these comments carefully. The main responses to these comments are shown in the following:

However, many key mechanisms are discussed by speculations without in-depth examination/comparisons to previous studies in the TP. This is because the study did not set clear objectives. Therefore, the title is also uncoordinated. For instance, do authors concern about the lake area (level) changes of Paiku Co? Figure 10 shows that lake level show small seasonal variation (within 1m), but do you think this is critical? Or, authors investigated large evaporation rate instead of previous studies? Readers can not understand how the Fig. 10 differs from other lake or even from ground in the TP. If the HESS request level of paper as scientific article instead of "report", I would like to suggest that paper needs fundamental revisions with clear objectives and results based on additional in-depth analysis.

Response: Substantial revisions, including both structure of the paper and Figures, have been made according to your comments in order to make the paper look more like a scientific paper instead of 'report'. The main changes include 1): remove sections 3.2 and 3.3 in the previous version; 2) move section 4.4 in the previous version to section 3.4 in the revision; 3) uncertainty estimation of lake evaporation according to hydrometeorology in the lake center; 4) combine Fig. 6-9 into Fig. 4 and Fig. 5 in the revision; 5) add precipitation and runoff in Fig. 6; 6) add a new Fig. 7 in the revision to show different amplitude of lake level changes.

We also try to address the main objective of this study more clearly in the revision (Line 60-65), that is to quantify lake evaporation during the entire ice free period using energy budget method and investigate its effects on seasonal lake level changes. Until now, lake evaporation during the late autumn and early winter is not typically investigated on the TP because it is difficult to install and maintain measurement platform due to the harsh natural conditions and the influence of lake ice. As a result, how lake evaporation affects seasonal lake level changes remains unclear due to lack of comprehensive observation of lake water budget.

We have added one paragraph in the introduction about the different amplitude of endorheic lake level seasonality on the TP (Line 42-51). 'Compared with numerous studies of inter-annual to decadal lake changes, seasonal lake level changes and the associated hydrological processes on the Tibetan Plateau (TP) are still less understood. Phan et al. (2012) showed that seasonal lake level variations in the southern TP are much larger than that in the northern and western TP. In-situ observations gave more details of seasonal lake level variations (Lei et al., 2017). One striking feature is the different amplitude of seasonal water level variations, that is, deep lakes usually exhibited considerably greater lake level variations than shallow lakes. For example, Zhari Namco and Nam Co, two large and deep lakes on the central TP (Wang et al., 2009, 2010), exhibited significant water level increase by 0.3~0.6 m during the summer monsoon season and a similar magnitude of lake level reduction by 0.3~0.5 m during post-monsoon season between 2010 and 2014. For the two nearby small and shallow lakes, Dawa Co and Bam Co, although there was a similar pattern of lake seasonality, the amplitude of seasonal lake level variations was considerably smaller than the two large and deep lakes (Lei et al., 2017).' The main causes for the different amplitude of lake level changes are still not investigated in previous studies, which is the main topic of our study.

We change the title of the paper to: 'Contrasting hydrological and thermal intensities determine seasonal lake level variations–A case study at Paiku Co in the central Himalayas'

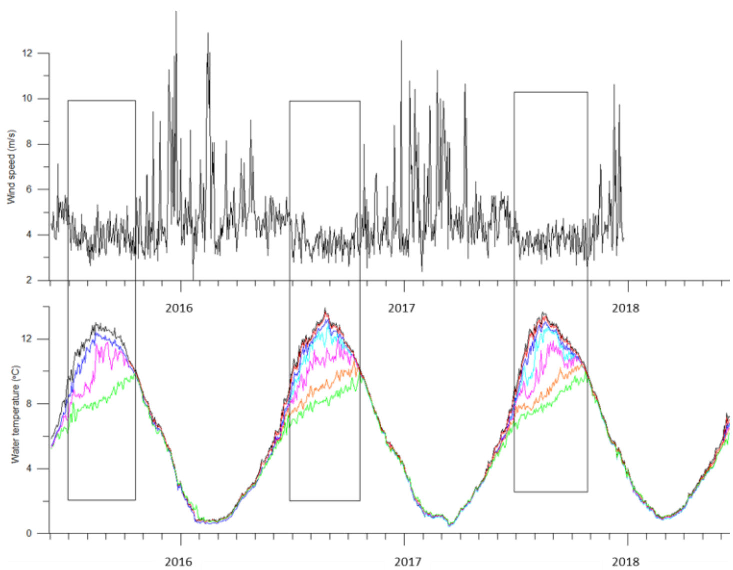
Seasonal variations of lake level and lake evaporation are shown in a new figure (Fig. 6) to show the contrasting hydrological and thermal intensities of Paiku Co.

Previous studies about lake evaporation on the TP have been reviewed and compared in Section 4.2 in the revision.

For the lake dynamics by means of hydrometeorology, following points need to be examined. 1) Water temperature profiles were almost homogeneity during Oct.- June (non-monsoon season), and author explained by "fully mixing" without any analysis. Please proof it physically using surface wind speed and variability conditions and water mixing theory. It is curious that such mixing occurred suddenly. In the central TP, large diurnal wind changes are found in winter due to the coupling of upper strong STJ and boundary layer development. Any relation to the seasonal change of atmospheric circulation ?

Response: Lake water temperature profile can be taken as a proxy of lake water mixing. In summer, the lake water is stratified due to the dramatic temperature gradient between surface and bottom. In autumn, the lake stratification is weakened gradually due to the decreased temperature gradient and intensified wind speed. From early October to later October, lake mixing was deepened gradually due to decreased temperature gradient and increase wind speed. Since the late October, the lake water is totally mixed as indicated by the disappearance of vertical temperature gradient. As we have addressed in the main text, the lake mixing is mainly forced by wind disturbance and water convection. This is also the common feature of lake water circulation, which has been addressed in many publications and books (i.e. Wetzel, 2001).

Clear Lake stratification at Paiku Co occurred in late June or early July, which corresponded to a significant reduction in wind speed. The lake stratification broke down in late October, which corresponded well to significantly increased wind speed. So lake water mixing may be related to seasonal changes in atmospheric circulation.



Comparison of lake water temperature and average wind speed. Daily wind speed at Qomolangma station is used.

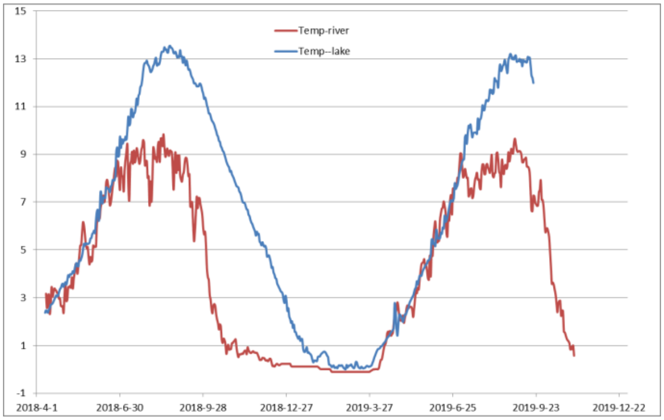
2) Seasonal change of water level should be explained by seasonal change of water budget, including precipitation, river runoff/inflow and surface water inflow. Even there are lack of areal in-situ measurements, some parameters could be estimated by previous studies or literature. This also links to Av calculation as mentioned in 3). I could not see precipitation *records, but the Rn sequence demonstrated that rain season is not clear compare to southern Himalayas and central plateau. If the impact of monsoon is small with fair/non-freeze weather, location of the lake may represent local dry climate behind the Himalayas where lee-side subsidence prevails, and that would characterize evaporation rate at Paiku Co.*

Response: We agree that seasonal lake level change should be explained by lake water budget, including precipitation, runoff etc. We have added a new Fig. 6 in the revision. Lake level, precipitation and runoff data are included (Fig. 6). Notably, we do not focus on all components of lake water budget in this study. The main purpose of this study is to quantify lake evaporation and its impact on seasonal lake level changes.

We agree that the impact of monsoon precipitation is small in this dry area and location of lake represent local dry climate behind the Himalayas where subsidence prevails. We have added this point in the site description in the revision (Line 80-83).

3) To consider the heat budget of the lake, especially for the condition of thermocline, advection of cold (snow/glacier-melt) water associated with river/surface inflow need to be considered. This paper only compares the heat budget at water surface, and conclude the evaporation as a ley parameter to affect lake level seasonality. Is there no effects of glacier melt water (they are illustrated in Fig. 1a) or monsoon precipitation inflow to establish lake temperature profile and lake level seasonality? Diurnal change of river level according to the glacier melt is observed by previous studies. There are some indication at the bottom temperature of northern point in Fig. 3b. At L115, please proof that Av can be ignored. Authors should not avoid those issues to analyze if they focus on the water cycle and environmental changes on the TP as introduced in Chapter. 1.

Response: We have added one paragraph in Section 2.3 to evaluate the impact of Av on the lake energy budget (Line117-123). Av can be estimated according to total river discharge (Fig. 1) and the water temperature difference between river and lake (data not shown). Lake water temperature was almost same to river water temperature between April and June, but 2-4^{o}C higher between July and December. As a deep lake, total river discharge to Paiku Co was about 800-900 mm water equivalent to lake level and accounted for 2-2.5% of total lake water storage. The river discharge can accumulatively decrease lake water temperature by ~0.1 ^{o}C in a year. Therefore, as a deep lake, the influence of river discharge and precipitation on the total lake heat storage at Paiku Co is very small and can be neglected. Therefore, we do not consider the influence of Av on the lake energy budget in this study.



Comparison of water temperature between Bulaqu river (red line) and Paik Co (blue)

We do not deny the contribution of precipitation and runoff in summer, there are very important for the rapid lake level increase in summer monsoon season. What we want to address in this study is the effect of high evaporation in autumn and early winter. Although solar radiation is already low in post monsoon season, high lake evaporation can lead to rapid lake level decrease due to the low runoff and precipitation during this period. Contribution of runoff to lake level increase in spring and summer is estimated in Table 3.

Minor comments:

There are no previous studies in Paiku Co. ? Need reviews.

Response: We give a review about previous studies at Paiku Co (Line 73-83). We did not do this because we have reviewed it in a previous publication (Lei et al., 2018).

Lei, Y., Yao, T., Yang, K., et al.: An integrated investigation of lake storage and water level changes in the Paiku Co basin, central Himalayas, J. Hydrol., 562, 599–608, 2018.

Water temperature sensors in the upper profile are shaded? Or, how deep the insolation can penetrate the water at the target lake?

Response: We do not think water temperature sensors in the upper profile are shaded. As we have illustrated in section 2.2, the first water temperature sensor were fixed below buoy at the water depth of ~0.5 m. The other sensors were fixed on the rope which was tied to an anchor at the lake bottom. The transparency of the lake is not measured until now.

L176AAˇ Small water temperature gradient is explained by cold air temperature. This is strange. Air temperature change is due to latent heat from the surface or advection. Enough radiation could increase the water temperature even the air temperature is cold with weak winds.

Response: We attribute it the relatively lower lake surface temperature in the revision.

L175-180 Those are speculations, not results.

Response: We have deleted this part in the revision.

L138 "input data were averaged at weekly interval. Does heat budget screened by the wind direction by instantaneous data then averaged?

Response: Wind speed and direction is not used during the calculation of energy budget and lake evaporation.

Units in Fig. 10 are mm/d, cm and it is m3/s in Table 3. Please unify them to capture accurate water balance.

Response: Thanks for pointing out this. We have unified the units (mm) in Fig. 6 in the revision.

Title of 3.3 "Lake hydrometeorology" is vague.

Response: We have merged it to section 3.2.

L215ãˇAAˇ "There was a 1.5 month lag between lake surface temperature and air temperature." Is not clear.

Response: We have deleted this part in the revision.

I could not understand the meaning to show the Fig.6.

Response: We have combined Fig. 6-9 into Fig. 4-5 in the revision.

L230 "Downward shortwave radiation at Paiku Co had an annual average of 251.8WÂ˘um-2 (Fig. 7), which is slightly higher than the TP average due to its lower latitude (Yang et al., 2009)." What is the TP average? Effects of Indian monsoon is stronger in southern TP in general, and cloudy weather may reduce the insolation. Or, the observation represent local weather in the valley?

Response: According to Yang et al (2009), downward shortwave radiation on the TP varies in a range of 150~290W/m^2, which is slightly lower than that at Paiku Co (190~290W/m^2). Although effect of Indian monsoon is stronger in the southern TP in general, mean annual precipitation at Paiku Co is only about 150-200 mm. So we agree that the observation represents the local dry climate behind the Himalayas where subsidence prevails (Line 82-83).

L230-237 Discussions are not clear due to mixture of seasonal change and annual average. Why the rainy season is not clear?

Response: As we have shown in Fig. 6, the rainy season is not clear because the precipitation at Paiku Co is low.

L17, L248,, "a deep lake". Many discussion attribute the characteristics to the depth of lake without examination. Manly lakes over the TP are shallower than the target lake? Please review that how the depth of lake over the TP characterize the lake temperature condition.

Response: As we have shown in section 4.2, seasonal changes in lake evaporation are significantly related to the mean lake water depth and the lake heat storage. The mean water depths of the lakes have been mentioned in section 4.2. Deep lake can store more energy in spring and summer and release more energy to the overlying atmosphere, which affects the season pattern of lake evaporation.

Response to reviewer #2

The manuscript "Thermal regime, energy budget and lake evaporation at Paiku Co, a deep alpine lake in the central Himalays" use in-situ measurements to analyze the energy budget components and obtain the evaporation amounts of Lake Paiku Co. As lake measurements are very limited on the Tibetan Plateau and most of the measurements are in the central or east parts of the Tibetan Plateau, the manuscript shows significance in describing clearly the thermal regime, energy budget and lake evaporation of a western lake on the Tibetan Plateau by in situ measurements. The structure of the manuscript is well-organized; the analysis of the processes are observation based and reasonable; I consider the manuscript to be appropriate to be published in the HESS journal after a minor revision. The detailed comments are given as belows:

Reply: Thanks for the positive comments. We have revised the manuscript according to your comments.

(1) In line 25-26ïijN˘ the last sentence in abstract seems has not clear connection with the other contents, I suggest to revise the sentence to keep it coherent with previous contents.

Reply: Thanks for the suggestion. We have revised this sentence to keep it coherent with the main purpose of the paper.

(2) In line 120-125, in equation (2), Ra is the downward longwave radiation to lake, while in equation (3) Ra is rewritten as the longwave radiation from lake. Here, in equation (3) and line 125, I think it should be Rw.

Reply: Thanks for pointing out this error. We will change R_a to R_w in Equation (3).

(3) In line 129-130, as daily averaged water temperature is used, in addition to the surface mixing by wind and convection, Here I suggest to add information that "there exists surface warming during the day and surface cooling at night for high elevation lakes, thus the two uncertainties by surface warming and cooling can cancel each other at a temporal resolution of daily."

Reply: Thanks for the good suggestion. We have added this information in the revision (Line 134-136).

(4) In line 161, I suggest to use "period" instead of "time" here; in line 262, it should be "in low values" rather than "in low value"; Figure 3 caption, "at different depths" rather than "at different depth"; Figure 4, a unit of (OC) should be added for the color bar.

Reply: Thanks for pointing out these errors. We have revised them in the revision.

Response to reviewer #3

Major comments:

Since the Tibetan Plateau has been one of the least studied areas, lake evaporation study in this region is welcomed and worth publication in HESS. However, I find there are substantial problems in this study. That is the accuracy of the evaporation in their study. I pointed out this issue in the review at the time of their previous submission. Unfortunately, they failed to solve this problem and the manuscript was rejected for publication. The authors have added new data at the lake center to compare their measurements on the shoreline. This is good. On the other hand, their treatment of the comparison is not enough to convince readers that their evaporation estimates are accurate and reliable.

Reply: Thanks a lot for your constructive and detailed comments about our submission. We have evaluated the uncertainty of lake evaporation at Paiku Co from the following aspects, net radiation, lake meteorological data (air temperature and humidity) in the shoreline, surface water temperature, and changes in lake heat storage.

The authors gave error estimates of evaporation in Section 4.2. They selected (1) net radiation and (2) water temperature differences between the northern and southern basins as the error sources. I think they should add other relevant error sources. They include, first, the use of air temperature and humidity on the shoreline instead of those above lake water. They compare the measurements on the shore and on the lake in Fig. 11 and conclude they are "very similar: : :.. data from the shoreline: : : can be used to represent the general condition of the whole lake: : :". This is new information and should be used to evaluate error from using onshore measurements. What they should do is to determine the RMS error of temperature and humidity measurements on the shore and used them to estimate errors of Bowen ration and sensible and latent heat fluxes. This can be added to the final error evaluation.

Reply: Thanks for the suggestion. We evaluate the error of air temperature and humidity the in the shoreline by comparing with those in the lake center. Generally, both air temperature and humidity in the shoreline are very close and fluctuated similarly with those in the lake center during the observing period, indicating that meteorological data in the shoreline can be used to calculate lake evaporation. RMS error of air temperature is estimated to 0.91 ^{o}C between center and shoreline during the observing period (23 September to 25 October 2019). RMS error of water vapor pressure is estimated to 0.069 kPa between shoreline and center.

The second error source they should consider is the use of water temperature instead of surface temperature. They claim that "the daily average between them is very similar: : :". But no supporting evidence is shown. In fact, previous studies do indicate a difference between the two even for mean values for day or longer. The authors should accept this and add this as one of the error sources for the evaporation estimates.

Reply: We agree that there is some difference between lake skin temperature and body temperature. Because it is still difficult to acquire long-term and continuous lake skin temperature in the lake center in such a deep lake like Paiku Co, we have to use lake water temperature at the depth of 0.4-0.8 m. To check the difference of lake skin temperature and body temperature, nighttime and daytime MODIS (MYD11A2) lake surface temperature in 2016 and 2017 is retrieved and compared with in-situ measurement of lake surface temperature. Generally, MODIS lake surface temperature is considered to reflect instantaneous lake skin temperature. Result shows that that lake skin temperature is higher than lake body temperature during daytime, and lower than lake body temperature during nighttime. The daily average water temperature used in this study is close to lake skin temperature because the lake water can be well mixed by the strong wind in the afternoon at Paiku Co. 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 spring and winter when the lake water gets cool, the skin temperature derived from MODIS data is about 0.05 ^{o}C higher than lake body temperature. Therefore, the difference of 0.6 ^{o}C between MODIS LST and in-situ observation data during a whole year is used to estimate the uncertainty of lake evaporation in the revision.

The third error source is the error in the energy storage estimation. To estimate energy storage, spatial mean water temperature profile, spatial mean water level, water level-volume relation, water level-surface area relation are needed. Since they are all based on some kind of measurement, there are always errors (measurement errors as well as sampling errors). They should be considered.

Reply: Thanks for the suggestions. Uncertainty in lake heat storage is mainly determined by errors in lake water storage and lake water temperature profile. Uncertainty of lake heat storage can significantly affect the seasonal distribution of lake evaporation. Uncertainty of lake water storage may result from 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. Assuming the uncertainty of the water depth is 1 m, the uncertainty of lake volume at Paiku Co is estimated to be 2.5%, according to the average water depth of ~40m. Using method of Qiao et al. (2018), uncertainty of lake water storage estimation at Paiku Co is estimated to 6% by comparing the reconstructed lake level and ICESat and CryoSat-2 satellite altimetry data between 2003 and 2018.

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. Journal of Hydrology, 578, 124052, 2019.

Minor comments:

Introduction. - The originality of the study: It is not clear what the original contribution of this study is. Authors claim that previous studies do not provide evaporation throughout a year. But in their study also, evaporation was not determined during the winter period. So it is not quite new. Please make it clear what is missing in previous studies and why their studies are needed based on a comprehensive review of previous studies. Also, these points should be reflected in discussion and conclusions

Reply: Thanks for the suggestion. The originality of our study mainly includes: 1) Lake evaporation at Paiku Co during the whole ice free period is investigated. In many previous studies, lake evaporation during the late autumn and early winter is not well studied because it is difficult to install and maintain measurement platform due to the harsh natural conditions and the influence of lake ice; 2) Changes in lake heat storage at Paiku Co are quantified and its impact on seasonal changes in lake evaporation is addressed. Changes in lake heat storage are not well studied for most lakes with eddy covariance method on the Tibetan Plateau, so its impact on seasonal changes in lake evaporation is not clearly addressed; 3) How lake evaporation affects seasonal lake level changes is investigated in this study. As introduced in the text, there is different magnitude of lake level seasonality, but the main causes for this remains unclear due to lack of comprehensive observation of lake water budget.

Importance of TP lakes. The authors explain the abundance of lakes in TP. Then authors should add relevance of these lakes for TP (or even for larger areas).

Reply: The importance of TP lakes has been addressed in the revision (Line 34-41).

Eddy correlation method. The authors mention that it is not suitable for long-term measurements. I believe this statement was correct perhaps 20 years ago. But it is easy to see the results of long-term measurements based on the eddy correlation method in the literature as well as datasets on the flux net sites.

Reply: We have deleted this paragraph in the revision.

Direct measurements of lake evaporation: I do not think the Bowen ratio method is in the category of direct measurements. It measures energy balance and evaporation is obtained only indirectly as one of the residuals of the energy balance equation. It relies on the similarity between temperature and humidity profiles.

Reply: We have deleted this paragraph in the revision.

- L96-97. ": : :therefore the meteorological condition over the lake surface can be recorded". This cannot be true without evidence. I made the same argument in previous reviews so please read it again. What I would suggest is to acknowledge that it is not the location where measurements should be made, but the measurements were used as a proxy of the above-lake measurements, and validity of this proxy will be discussed in section: : :(see major comment)

Reply: Thanks for the suggestions. We have addressed this in the revision according to your suggestion. We agree that it is not the location where measurements should be made and the measurement was used as a proxy of above lake measurements in the revision (Line 99-101).

- L106 "weekly averaged radiation..."; What are the possible errors to apply the Bowen ratio method with weekly averaged data? The Bowen ratio equation (4) was derived from two profile equations of H and LE. Profiles equations derived by applying the similarity theory are valid for the steady-state condition under certain stability. So we generally apply them for 30-min to hourly mean values. For practical purposes, we apply them for daily data assuming neutral stability but strictly speaking, this is not valid since profile equations are not linear and therefore simple time averaging does not yield valid equations for the given averaging period.

Reply: In this study, daily Bowen ratio is calculated. Weekly averaged radiation was used to calculate lake evaporation in order to reduce the error caused by regional difference. Weekly evaporation is calculated according to the weekly Bowen ratio.

- L114-115. "the influence of river discharge: : :can be neglected" You cannot say this without supporting evidence. The authors should give and compare lake storage and river discharge.

Reply: The influence of river discharge on lake energy budget has been discussed in the revision (Line 118-124). Av can be estimated according to total river discharge (Fig. 1) and the water temperature difference between river and lake (data not shown). Lake water temperature was almost same to river water temperature between April and June, but 2-4^{o}C higher between July and December. As a deep lake, total river discharge to Paiku Co was about 800-900 mm water equivalent to lake level and accounted for 2-2.5% of total lake water storage. The river discharge can accumulatively decrease lake water temperature by ~0.1 ^{o}C in a year. Therefore, as a deep lake, the influence of river discharge on the total lake heat storage at Paiku Co is very small and can be neglected. Therefore, we do not consider the influence of Av on the lake energy budget in this study.

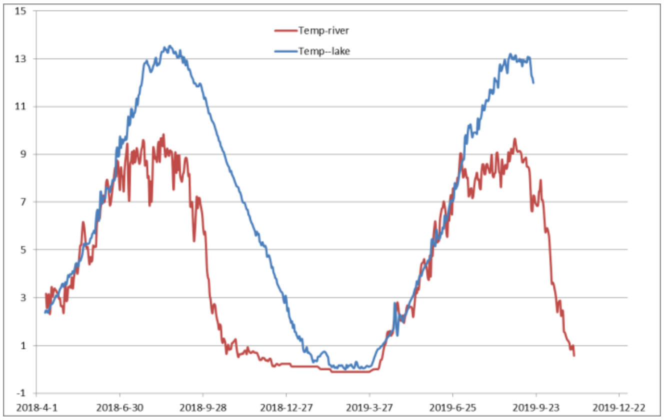


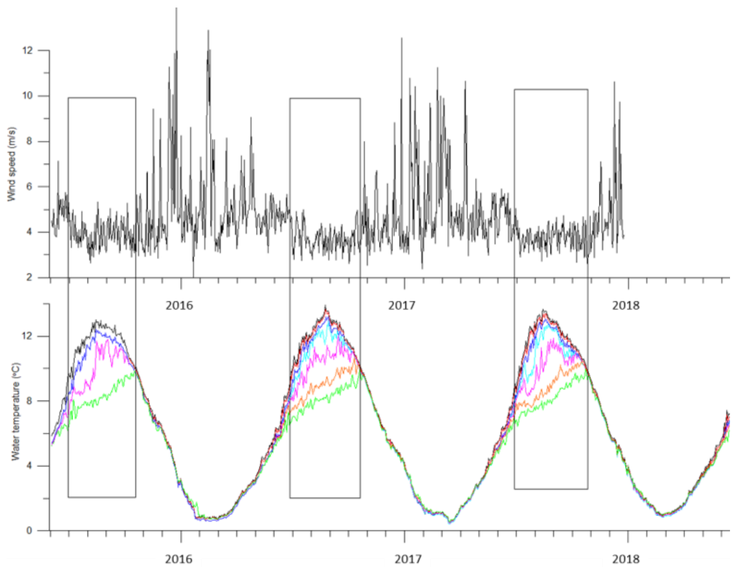
Fig. S2. Comparison of water temperature between Bulaqu river (red line) and Paik Co (blue)

- L114-115. ": : :therefore: : :we do not consider : : :G.." There is no mention of the reason why G can be neglected.

Reply: We do not considered the heat transfer between lake water and bottom sediment in this study because there is no data available.

- L153-155, ": : :reduction in wind speed (data not shown)"; As I recall from the reply of authors to the reviewers' comments in the previous version, authors do not have wind speed data. Then the statement of "data not shown" is misleading. When we see this statement, we tend to believe that there were data and authors checked them to validate what is written in the manuscript even though they are not shown in the manuscript with a figure or a table. If you do not have data, then you should not mention wind influence as if it was based on data. There are similar statements on wind speed here and there in the manuscript. Authors need to remove them or change expressions. Alternatively, authors could rely on wind speed from reanalysis data. However, the reliability of any reanalysis data set should be established first (perhaps by referring to previous studies) for the study area before they can use the reanalysis data.

Reply: Here wind speed at Qomolangma station is used to compare with lake surface temperature changes. Qomolangma station is located at the northern slope of Mount Everest, about 150 km east of Paiku Co. If this data is just used as a simple comparison, this is no problem because it does not need high accuracy. But if wind speed at Qomolangma station is used to calculate lake evaporation, maybe it has too large spatial difference.



Comparison of lake water temperature and average wind speed. Daily wind speed at Qomolangma station is used.

- L179 "..but also the bottom water"; I do not understand what authors want to claim.

Reply: We have deleted this sentence in the revision.

- L200-201; "....Lower temperature gradient caused stronger water convection....."; I do not understand the logic in this part. I assume water convection is stronger when the vertical gradient is larger.

Reply: According to my knowledge, water convection is weaker when the temperature vertical gradient is larger. For example, water convection is weaker in August when the temperature vertical gradient is large, because the lake water is stratified. Similarly, water convection is strong in winter when the temperature vertical gradient is weak because the lake water is mixed.

- L204-205 "(Fig.1)"; Fig. 1 shows the locations of water level loggers but authors are talking about water temperature. In Fig.1, there are also the locations of water temperature measurements. This is confusing.

Reply: We have revised the caption of Fig. 1. HOBO water level logger can not only record water level changes, but also water temperature changes.

- L208-209 "....large errors can result if only water temperature data collected at the shoreline are used to calculate lake heat storage and energy budget."; Similarly, errors can result if only water temperature data collected at the center of the lake are used. The authors should acknowledge this possibility to make analysis accordingly (see major comment).

Reply: We have deleted this paragraph in the revision.

- L223 " Indian summer monsoon precipitation"; there is no mention of heat advection due to precipitation in the application of the Bowen ratio method. All energy sources that are used for the turbulent neat fluxes should be considered and mentioned.

Reply: The influence of heat advection due to precipitation on lake energy budget has been mentioned in the revision (Line 118-124).

- L257-259 " Negative value...., indicating the lake water absorbed energy from the overlying atmosphere. Positive value...., indicating the lake water released energy to the overlying atmosphere." These statements are not correct. The sign of the Bowen ratio simply indicates whether the fluxes are in the same direction (positive), or different direction (negative).

Reply: We have deleted this sentence in the revision.

- L274-276 " Lake evaporation between middle January and April is not determined... "; Why not? The authors do give latent heat flux for this period. If it is not certain whether the lake surface is covered with solid water or liquid water, then authors could give two values of evaporation. One in the case of the ice surface, and another one in the case of liquid water surface. The true evaporation is somewhere in between. This can be used together with the evaporation estimate obtained by assuming it is the same as water level change in L290-291.

Reply: We have addressed these sentences in more detail (Line 220-222). We do not determine lake evaporation between January and April because the lake surface is sometimes covered by ice. Energy budget over the lake surface during ice covered season is different from that without lake ice.

- L288 ".....lake ice can effectively prohibit evaporation."; Is this true? How about sublimation? Is the latent heat flux on ice-covered lake zero? The authors could add references to support their statement.

Reply: We agree that lake water can still get lost through sublimation. We have revised this sentence in the revision (Line 256-257).

- L290-291 "Assuming lake evaporation between January and April is equal to lake level decrease ..."; the Authors should provide an error estimate of evaporation based on this assumption. Errors due to lake level measurements, mean lake water level estimation, water level-volume relation, water level-lake surface area relation, etc.

Reply: Thanks for the good suggestion. We do not consider the lake evaporation between January and April in the revision.

- L293 "20.4%"; the Authors should explain how this ratio was derived.

Reply: We have deleted this sentence in the revision.

- L299 "We set up a platform in the southern centre of Paiku Co"; The location should also be shown in Fig.1

Reply: We have shown the location of the platform in Fig. 1 in the revision.

- L302 "....fluctuated very similarly between..."; This is a subjective statement. In fact, I do not quite agree that they are VERY similar. A better presentation would be the determination of the difference between the two measurements and its error propagation into Bowen ratio and flux estimates (see major comment).

Reply: Thanks for the suggestion. We have quantified the difference of the two data (Line 278-280).

- L303 "...can be used to represent the general condition of the whole lake..."; This statement is based on a superficial analysis. It should be based on the error propagation analysis mentioned above (see also major comment).

Reply: We have quantified the difference of the two data (Line 278-280).

- L318-319 "Although there is some spatial difference, the similar seasonal patterns of energy budget and lake evaporation at different sites indicate that our results are reliable."; Just like L208-209, authors should acknowledge the difference and estimate the magnitude of the error due to spatial difference, rather than ignoring the difference by simply saying "reliable". In fact, authors do give error estimates in L329-344. Thus the statement of "reliable" is not quite consistent with the error estimates.

Reply: We have deleted this paragraph in the revision.

- L320, Section 4.2. Here authors should give all possible error sources and their likely magnitude, and use them to give a total error in their evaporation estimates. They should include, among others, the error due to the use of temperature and humidity measurements at the shoreline. Also, when they talk about annual evaporation, there are possible errors due to the assumption in L290-291 (see major comment).

Reply: Please see the reply to the major comment.

- L326 "very similar seasonal fluctuations (R2=0.55....with standard deviation of 23.9 WÂ°um-2.)"; With Rˆ2=0.55, I do not think it is VERY similar. Why the standard deviation? ãˇAAˇRMS error is a more appropriate indicator of the similarity.

Reply: We have quantified the difference between the two dataset. RMS error between the two data is estimated.

- L326-327 " Assuming approximately 70% of the net radiation was consumed by lake evaporation (Lazhu et al., 2016)........ 74.5 mm per year "; This percentage is from a different lake. Why not use estimates for Paiku Co. given in Table 2? The authors should explain how 74.5 mm/year was derived.

Reply: We have deleted this sentence in the revision.

- L345- " Uncertainty of lake evaporation in this study was also validated by comparing lake level changes"; Just like the case in L290-291, authors should provide error estimates for the evaporation estimates based on lake level measurements. Possible advection due to precipitation should be addressed as commented above for L223.

Reply: Thanks for the good suggestion. Lake level changes can be measured accurately (<1 cm), so error estimated is not considered in this study. Precipitation is also not considered because it is usually very low in winter season.

- L352 "As shown in Table 3, runoff at the three large rivers can contribute to lake level increase by 0.71.6"; Runoff values in Table 3 are for a short period. Can you use them to estimate monthly runoff?

Reply: Monthly lake runoff at Paiku Co can be estimated based on this measurement, but with large uncertainty. Therefore, we just use daily runoff in this paper.

- L355 "To further explore the impact of lake heat storage on the seasonal pattern of lake evaporation...."; Authors should summarize at the end of section 4.3, what kind of new findings were obtained on the impact of heat storage to lake evaporation from their measurements/analyses and comparison with previous studies. The phase shift of lake evaporation due to lake heat storage is in a way common knowledge. We would like to hear something new here. How about differences among the TP lakes? For example, in the introduction, the authors mention the difference of lake size change between the interior TP and southern TP. Any new findings on this point? Also try to make clear the relation between the statements made in the introduction (e.g., L58-67) and those in this section. You do not have to say similar things in different parts of the manuscript.

Reply: We have added a new section 3.4, Fig.6 and Fig.7 in the revision. The main findings are summarized in section 3.4 (Line 233-237). 'Fig.6a shows that positive lake water budget at Paiku Co mainly occurred during the summer monsoon season (Jul. and Aug.), while negative water budget mainly occurred during the post monsoon season (Oct. to Dec.). Precipitation and lake inflow are mainly concentrated during the summer monsoon season, meanwhile lake evaporation is relatively low (Fig. 6b, c), which together leads to the rapid lake level increase (40~60 cm). During the post monsoon season, precipitation and lake inflow are already very low, meanwhile lake evaporation is in its high value, which leads to rapid lake level decrease (~40 cm). Contrasting hydrological and thermal intensities play an important role in the seasonal lake level variations of Paiku Co.'

- Section 4.3; In addition to comparison with other lakes in TP, authors may want to address the difference of the TP lakes in comparison with other lakes in the world. What are special about the TP lakes? Are there similar lakes in other parts of the world? What are the controlling factors to make them similar/different?

Reply: In this study, we mainly focus on lakes on the TP (section 3.4). We add Fig.7 to show this phenomenon at other lakes on the TP.

- L359 "2011-2012", L362 "2013-2015"; Evaporation estimates for these periods are continuous even during the winter season? Clarify this in the manuscript since there is a statement in the introduction saying "lake evaporation throughout the year is not typically investigated".

Reply: We have clarified this in the revision. As we have addressed in the introduction, lake evaporation derived from eddy covariance during winter season is not investigated at most of the previous studies. Lake water temperature profile and changes in lake heat storage are also not investigated. An except is Qinghai Lake, where water temperature at only the upper 3 m was investigated, but the whole water temperature profile is still unclear.

- Fig.1; Add a scale, latitude/longitude to the lower right figure of the panel a.

Reply: We have revised Fig.1 according to the suggestion.

- Fig.5 caption; "depth of 0 m"; should it be 0.4 m?

Reply: We have deleted this figure in the revision.

- Fig. 9; Change the solid line into a dotted line when there are missing values for an extended period.

Reply: Thanks, we have revised this Figure.

- Fig. 10; what are the spikes in the evaporation values? They are weekly values so that they look strange. The authors should explain this in the main text (perhaps in connection with error estimates).

Reply: The spikes in the evaporation values may come from changes in lake heat storage. Changes in lake storage mainly depend on lake water temperature change, which is measured at an interval of 5-10m. So, large water temperature changes can cause large changes in lake heat storage and spikes of lake evaporation. If lake water temperature on vertical profile is measured more densely, changes in lake heat storage can be quantified more accurately.

- Fig. 11; explain in the main text what the averaging period of the plotted data is.

Reply: We have addressed this in Fig.8 in the revision.

- Table 1; add information on GMX600.

Reply: Thanks for the suggestion. We have added information about GMX600 in Tab.1 in the revision.

Contrasting hydrological and thermal intensities determine seasonal lake level variations – A case study at Paiku Co in the central Himalayas ~~Thermal regime, energy budget and lake evaporation at Paiku Co, a deep alpine lake in the central Himalayas~~

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Abstract. ~~Endorheic lakes on the Tibetan Plateau (TP) experienced dramatic changes in area and volume during the past decades. However, the hydrological processes associated with lake dynamics are still less understood.~~ Evaporation from hydrologically-closed lakes is one of the largest components of lake water budget ~~on the Tibetan Plateau (TP)~~, however, its effects on seasonal lake level variations remain unclear due to lack of comprehensive observations on the Tibetan Plateau (TP). In this study, lake evaporation and its effects on seasonal lake level variations ~~and its impact on seasonal lake level changes~~ at Paiku Co, central Himalayas, ~~were~~ were investigated~~-~~ through energy budget method based on ~~three years of~~ in-situ observations of lake thermal structure and hydrometeorology (2015-2018). The results show that~~, as a deep alpine lake,~~ the seasonal pattern of heat flux over the lake surface was ~~considerably~~significantly affected by the~~higher in~~~~Paiku Co is a dimictic lake with thermal stratification between July and October.~~ ~~post monsoon season (Oct. to Dec.) than that in pre-monsoon and monsoon seasons (Apr. to Jul.) due to the impact of~~~~As a deep alpine lake, the large heat storage significantly influenced~~ large lake heat storage ~~the seasonal pattern of heat flux over lake surface~~. Between April and July~~Between April and July~~, ~~when the lake gradually warmed,~~ about 66.5% of the net radiation was consumed to heat lake water. Between October and December, ~~Between October and January, when the lake cooled,~~ heat released from lake ~~water~~ surface to the overlying atmosphere was about 3 times larger than the net radiation. There was ~5 month lag between the maximum lake evaporation and maximum net radiation ~~at Paiku Co~~. Lake evaporation at Paiku Co was estimated to be 975±96 mm during the ~~entire~~ ice free period (May to Dec~~.~~), characterized by low values during the pre-monsoon and monsoon seasons and high values during the post-monsoon season. Contrasting hydrological and thermal intensities at Paiku Co play an important role in the seasonal lake level variations. Relatively low lake evaporation but high lake inflow led to rapid lake level increase during the summer monsoon season. ~~.~~In contrast, high lake evaporation and low lake inflow led to the dramatic lake level decrease during the post-monsoon season. ~~This seasonal pattern of lake level changes can also be found in other deep lakes~~

~~on the TP.~~ While for shallow lakes, lake level does not exhibit large seasonal fluctuations due to the similar seasonal pattern of lake evaporation and lake inflow.

~~Lake evaporation was estimated to be 975±82 mm between May and December, with low values in spring and early summer, and high values in autumn and early winter. The seasonal pattern of lake evaporation at Paiku Co significantly affected lake level seasonality, that is, a significant lake level decrease of 3.8 mm/day during the post-monsoon season while a slight decrease of 1.3 mm/day during the pre-monsoon season. This study may have implications for the different amplitudes of seasonal lake level variations between deep and shallow lakes.~~

1 Introduction

~~Lake not only plays an important role in global hydrological and biogeochemical cycle, but also serves as important water resources including drinking water supply, agricultural production, recreation and fisheries (e.g. Lehner and Döll, 2004). Lake is also of vital importance in sustaining regional ecological balance as being home for organism such as macrofauna, vegetation and microbe (e.g. Hoverman et al., 2012). Lakes additionally influences regional climate. For example, due to different heat properties between lake water and the land, lake water plays a cooling role in summer and warming role in winter (Scott and Huff, 1996). As such, investigations of lake water and energy budgets, which provide basic information regarding the loss and gain of water and energy, are important in ascertaining the role of lakes in local to regional scale communities (Sugita et al., 2019).~~

The Tibetan Plateau (TP) hosts the greatest concentration of high-altitude inland lakes in the world. More than 1200 lakes (>1 km^2) are distributed on the TP, with a total lake area of ~~~~~more than 45000 km^2 in the 2010s (Ma et al., 2011; Zhang et al., 2014a). During the past decades, lakes on the TP experienced significant changes in response to climate warming and wetting, glacier mass loss and permafrost thawing (Lei and Yang, 2017). Most lakes on the interior TP expanded dramatically since the late 1990s, in contrast with lake shrinkage on the southern TP (e.g. ~~Liu et al. 2009;~~ Lei et al., 2013, 2014~~; Song et al. 2013; Zhang et al. 2014a; Crétaux et al. 2016; Yang et al., 2016~~). For most ~~L~~lakes across the TP, lake water temperature increased ~~dramatically in response to climate warming~~ (Zhang et al., 2014b; Su et al., 2019~~).~~) and ~~L~~lake ice duration shortened considerably in response to rapid climate warming during the past decades ~~across the TP~~ (Kropacek et al., 2013; Ke et al., 2013; Cai et al., 2017).

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

Evaporation from hydrologically-closed lakes is one of the largest components of lake water budget~~Evaporation is one of the largest components of lake water budget~~ (Li et al., 2001; Morrill, 2004; Xu et al., 2009; Yu et al., 2011). Direct measurements of lake evaporation were usually conducted ~~by using~~through the eddy covariance system or energy budget method (~~e.g.~~ 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). ~~Eddy covariance is a more direct means of measuring lake evaporation, but it is difficult to perform and requires specialized and expensive instrument, which makes it more suitable for short-term observations (Giannoiu and Antonopoulos, 2007; Rouse et al., 2003, 2008). Although the energy budget method also needs costly instrumentation and significant personnel commitment for fieldwork, it is more suitable for accurate, long-term monitoring (Winter et al., 2003).~~

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 ~~the~~ 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, energy budget over the lake surface is seldom investigated due to the lack of in situ measurements of lake thermal structure on the TP. ~~However, lake evaporation throughout the year is not typically investigated because it is difficult to install and maintain measurement platform due to the harsh natural conditions on the TP and the influence of lake ice during the late autumn and early winter. As a result~~As a result, how lake evaporation affects seasonal lake level ~~changes~~ variations on the TP remains unclear~~due to the lack of comprehensive observations of lake water budget on the TP~~.

To ~~understand~~ quantify lake evaporation and its effects on seasonal lake level changes~~lake water budget and the associated lake level changes~~on the TP, we conducted comprehensive in situ observations at Paiku Co in the central Himalayas since ~~2013~~2013, including lake level, water temperature profile, runoff and hydrometeorology etc. In this study, lake evaporation at Paiku Co during the ice free period is investigated though energy budget method. ~~we~~ 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 ~~hydro-meteorology and~~ energy budget and heat flux over the lake surface, and finally analyse the seasonal pattern of lake evaporation and its ~~effect~~ impact on seasonal lake level changes.

2 Methodology

2.1 Site description

Paiku Co (85°35.12′ E, 28°53.52′ N, 4590m a.s.l) is located in the north slope of the central Himalayas. The lake has a surface area of 280 km^2 and watershed area of 2376 km^2. Bathymetry survey showed that Paiku Co has mean water depth of 41.1 m with the maximum water depth of 72.8 m (Lei et al., 2018). The lake is hydrologically closed and lake salinity is about 1.7 g/L. Glaciers are well developed to the south of the Paiku Co, with a total area of ~123 km^2. Dozens of paleo-shorelines are visible around Paiku Co. The highest shoreline is ~80 m above the modern lake level. Wünnemann et al. (2015) found that there was a close relationship between glacier dynamics and lake level changes since the Last Glacial Maximum (LGM). The lake has been shrinking since the 1970s (Nie et al., 2013; Dai et al., 2013). Between 1972 and 2015, lake levels at Paiku Co decreased by 3.7 ± 0.3 m and water storage reduced by 8.5 % (Lei et al., 2018). According to rain gauge data collected between 2013 and 2016, ~~seasonal and~~ 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^{o}C between June ~~5,~~ 2015 and ~~June 4,~~May 2016 (Lei et al., 2018).

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2.2 Data acquisition

In situ observations, including lake water temperature profile and hydro-meteorology ~~over lake surface~~, were carried out in Paiku Co basin. HOBO water temperature loggers (U22-001, Onset Corp., USA) were used to monitor water temperature ~~profile~~ with an accuracy of ±0.2 ^{o}C. Two water temperature profiles were installed in Paiku Co's southern (0-42 m in depth) and northern (0-72 m in depth) basins (Fig. 1). In the southern basin, water temperature was monitored at the depths of 0.4 m, 5m, 10 m, 15 m, 20 m, 30 m and 40 m. In the northern basin, water temperature was monitored at the depths of 0.4 m, 10 m, 20 m, 40 m, 50 m, 60 m and 70 m. Since lake level fluctuates seasonally, the depth of water temperature loggers may also have changed in a range of 0.4-0.8 m. Water temperatures were recorded at an interval of 1 hour and daily-averaged values were used in this study. Three years' observational data from June 2015 to May 2018 from the southern basin was acquired, while only one year's data (June 2016 and May 2017) from the northern basin was acquired.

>>Fig. 1<<

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

~~>>Fig. 2<<~~

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~~(87 °1.22′E, 28 °25.23′N, 4276 m a.s.l)~~. The 2 m air temperature, relative humidity, wind speed, radiation were recorded at an interval of 10 min. In this study, downward shortwave radiation and longwave radiation at this station were used because the climate conditions between Paiku Co and Qomolangma station were very similar, including topography, altitude, cloud cover etc. Nonetheless, weekly averaged lake evaporation ~~radiation~~ was calculated ~~used to calculate lake evaporation~~ in order to reduce the radiation error caused by regional difference. The related information about hydro~~-~~meteorology observations at Paiku Co basin are listed in Table 1.

2.3 Energy budget derived lake evaporation

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

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

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, ~~S~~ G is ~~the~~ change in lake ~~water energy~~heat storage, ~~G~~ S is the heat transfer between lake water and bottom sediment, and A_V is the energy advected into lake water. The units used for the terms of Eq (1) are $W{\cdot}m^{-2}$.

Av was estimated using total river discharge and the water temperature difference between river and lake. Lake water temperature was almost same to river water temperature between April and June, but 2-4°C higher between July and December (data not shown). As a deep lake, total river discharge to Paiku Co was about 800-900 mm water equivalent to

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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. Therefore, as a deep lake, the influence of river discharge and precipitation on the total lake heat storage at Paiku Co is very small and can be neglected. Therefore, we do not consider the influence of G and A_V on the lake energy budget in this study. ~~As a deep lake, the influence of river discharge on the total lake heat storage at Paiku Co is very small and can be neglected. Therefore, we do not consider the influence of G and A_V on the lake energy budget in this study.~~

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

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

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

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

$$R_{\cancel{a}w} = \varepsilon_a \times \sigma \times (T_w + 273.15)^4 \quad (3)$$

where ~~R_a is the longwave radiation from lake,~~ σ is the Stefan-Boltzmann constant ($=5.67\times10^{-8}\ W \cdot m^{-2} \cdot K^{-4}$), ε_a is the water emissivity (0.97 for water surface) and T_w is lake surface ~~water~~ temperature ~~of the lake~~ (°C). In this study, the water temperature at the depth of 0.4-0.8 m was used to represent the lake surface ~~water~~ temperature ~~because the surface water temperature was not monitored~~. ~~Although the water temperature at the depth of 0.4-0.8 m does not represent 'skin' temperature (Prats et al., 2018), the daily average between the two is very similar because surface water can be mixed quickly by wind in the afternoon.~~ There exists surface warming during the day and surface cooling at night for high elevation lakes (Prats et al., 2018), thus the two uncertainties by surface warming and cooling can cancel each other at a temporal resolution of daily.

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

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

where β is Bowen ratio, ~~T_s~~ T_w is the surface water temperature (°C), T_a is air temperature at 2m high above the water surface (°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, $6.5\times10^{-4}\ ^{o}C^{-1}$. In this study, air temperature, air pressure and specific humidity were monitored at the lake's shore. Saturated vapour pressure at the lake surface was calculated according to surface water temperature in the ~~southern~~ lake ~~center~~centre ~~of the lake~~. To match the radiation, all the input data were averaged at weekly interval before lake evaporation was calculated.

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

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

where c_w is the specific heat of water (J·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). ~~S~~ G was calculated at an interval of 5 m and therefore there are 13 layers in vertical direction. ΔV_i was acquired according to the 5m isobath of Paiku Co (Lei et al., 2018). ΔT_i was calculated at 5 m interval as the average temperature of the top and bottom layer. Changes in lake heat storage for the bottom water (>40 m) in 2015/2016 and 2016/2017 were calculated according to the data in 2016/2017 since there is no data in the other two years.

3 Results

3.1 Thermal structure of lake water

Water temperature profiles between 2015 and 2018 show that Paiku Co was thermally stratified between July and October, and fully mixed between November and June in each year of the study period (Fig. ~~3~~2). Lake water temperature increased rapidly from 2 to 7 ^{o}C between April and June due to the strong solar radiation. During this warming period, water temperature ~~differences between~~between the lake surface and bottom ~~water~~ was ~~less than 1 ^{o}C~~almost same, indicating the lake water was well mixed. The temperature gradient on vertical profile increased ~~dramatically~~ considerably in the late June ~~with~~ and clear stratification occur~~ring~~red ~~in~~ since July~~,~~. ~~which~~ The occurrence of thermal stratification corresponded to a significant reduction in wind speed (data not shown) ~~(data not shown)~~. Strong lake surface heating and the reduction in wind speed together contributed to the development of thermal stratification (Wetzel, 2001). During the summer stratification period, the surface water warmed rapidly from 7 to ~13 ^{o}C between July and August, while the bottom water warmed much more slowly. As a result, the surface water reached to its highest temperature in the late August while the bottom water (>40 m) reached to its highest temperature in the middle to late October. ~~t~~The thermocline formed between 15 m and ~~30~~ 25 m water depth, with the largest temperature difference of 5~6 ^{o}C ~~occurring~~ 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. ~~3~~2). As a result, the water temperature gradient on vertical profile decreased, which weakened the ~~caused the~~ lake stratification and deepened the mixed layer. The lake stratification~~to~~ totally ~~break~~ broke down in the late October of each year~~. Notably, the timing of the stratification breaking down,~~, correspond~~ed well~~ing to significantly increased wind speed during this ~~time~~ period (data not shown). ~~Unlike the rapid appearance of lake stratification in late June~~Notably, the breakdown of stratification occurred ~~more~~ gradually, with the mixed layer deepening gradually throughout October (Fig. ~~4~~3). T~~T~~he mixed layer reached to 40 m water depth on October 13th, 2016, and to 70 m water depth about two weeks later (October 30th). Following the complete breakdown of the water column's stratification, the bottom water experienced rapid warming in several days due to its mixture with the warmer water from the upper layer. For example, the water temperature at 70 m water depth remained stable at ~6.9 ^{o}C from July to October, but increased abruptly from 6.9 to 8.6 ^{o}C in less than one week~~s~~ (October 25th to ~~October~~ 30th).

Paiku Co's water column was fully mixed ~~again between~~ since November ~~and May~~ as indicated by the identical lake water temperature profiles at the two monitoring sites (Fig. ~~3~~2, Fig. ~~4~~3). 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.

~~Landsat satellite images show that Paiku Co did not completely freeze up in winter during the study period, therefore lake water stratification in winter did not appear as reported in other studies on the TP (Wang et al., 2019).~~

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

~~As a deep lake, Paiku Co stored a large amount of energy in spring and summer and released it in autumn and early winter. The identical lake water temperature profile between November and June at Paiku Co indicates that changes in lake heat storage are not only affected by surface water, but also the bottom water. For deep lakes like Paiku Co, changes in lake heat storage can be significantly underestimated if only the surface water is considered.~~

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

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

3.~~4~~ 2 ~~Impact of~~ ~~Changes in lake heat storage~~Energy budget over the lake surface ~~on the heat fluxes~~

The main components of energy budget over the lake surface, ~~Changes in lake heat storage at Paiku Co were can be quantified using in-situ observations of water temperature profile and detailed lake bathymetry. , which~~ ~~This also makes it possible to evaluate the impact of lake heat storage on the heat flux at lake surface (Fig. 8).~~ ~~Radiation,~~ including downward shortwave radiation, downward longwave radiation to lake and upward longwave radiation from the lake body, ~~is~~are shown in Fig. ~~7~~4a-c. Downward shortwave radiation ~~at Paiku Co~~ had an annual average of 251.8 W·m^{-2} (Fig. ~~7~~4), which is slightly higher than the TP average due to its lower latitude (Yang et al., 2009). Downward and upward longwave radiation over the lake surface ~~to the lake~~ had an annual average of 235.8 W·m^{-2} ~~. Upward longwave radiation from the lake body had an annual average of~~and 336.8 W·m^{-2}, respectively. The net radiation over Paiku Co varied seasonally ~~between~~in a range of 19.0 ~~and~~ ~212.1 W·m^{-2}, with an average value of 125.8 W·m^{-2}. Relatively high net radiation occurred from April to August (200.4 W·m^{-2}), with the highest value in June (212.1 W·m^{-2}). Relatively low net radiation occurred from October to February (52.2 W·m^{-2}), with the lowest value in December (19.7 W·m^{-2}).

>>Fig. ~~7~~4<<

Changes in lake heat storage at Paiku Co were quantified using in-situ observations of water temperature profile and detailed lake bathymetry (Fig. 4e), which makes it possible to evaluate the impact of lake heat storage on the heat flux over the lake surface ~~(Fig. 4e).~~ Between April and July when Paiku Co warmed gradually, the lake water absorbed energy at an average

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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 ~~the~~ its highest. Between October and January, when ~~Paiku Co~~the lake water cooled, the lake ~~heat storage decreased and~~ 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 heat flux at lake surface was determined as the difference between the net radiation and changes in lake heat storage. The lowest heat flux occurred in June and the highest in November, which is consistent with the seasonal pattern of changes in lake heat storage. The seasonal pattern of heat flux at Paiku Co is almost anti-phase with the net radiation (Fig 8B). There was a ~5 month lag between the maximum heat flux and maximum net radiation due to the large heat storage of lake water. Although net radiation was high in the late spring and summer, a large portion of energy was consumed to heat lake water, which resulted in low heat flux over the lake surface. In the autumn and early winter, although net radiation was relatively low, a large amount of heat stored in the lake was released into the overlying atmosphere, which resulted in high heat flux.~~

~~>>Fig. 8<<~~

~~The Bowen ratio determines the distribution of sensible and latent heat flux. At Paiku Co, the Bowen ratio varied in a range of -0.26~+0.37, with an annual average value of +0.08 (Fig. 9, Tab. 2). Negative value occurred between April and July, with an average value of -0.12, indicating the lake water absorbed energy from the overlying atmosphere. Positive value occurred between August and January, with an average value of 0.20, indicating the lake water released energy to the overlying atmosphere.~~

~~Latent heat flux is 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 value between May and June, with an average of 38.7 W·m^{-2}, and high value 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 vapor pressure difference between the lake surface and the overlying atmosphere (r^2=0.41). 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} (Fig. 9b), and was in positive value between August and December with an average of 23.0 W·m^{-2}. There was a high correlation between sensible heat and the water temperature difference between surface water and the overlying atmosphere (r^2=0.86).~~

~~>>Fig. 9<<~~

3.~~5~~ 3 Lake evaporation ~~at Paiku Co~~

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~~, with an annual average value of +0.08~~ (Fig. ~~9~~5c~~, Tab. 2~~). Negative values occurred between April and July,

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with an average value of -0.12. Positive values occurred between August and December, with an average value of +0.20. Latent heat flux ~~i~~was the main component of heat flux, with an average value of 112.3 $W\cdot m^{-2}$ between May and December. The latent heat was in low values between May and June, with an average of 38.7 $W\cdot m^{-2}$. High values occurred between October and December, with an average of 153.3 $W\cdot m^{-2}$ (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 $W\cdot m^{-2}$, accounting for ~11% of latent heat flux. Sensible heat flux was negative between April and July with an average value of -5.6 $W\cdot m^{-2}$ (~~Fig. 9b~~Tab.2), and was in positive value between August and December with an average of 23.0 $W\cdot m^{-2}$. 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<<

~~>>Fig. 9<<~~

Lake evaporation at Paiku Co ~~between May and December~~during the ice-free season is shown in Fig. ~~10~~6b. Lake evaporation was generally low ~~between~~ in May and June with an average value of 1.7 mm/day. In July and August, lake evaporation increased rapidly from 2.9 to 4.1 mm/day. High lake evaporation occurred between September and December, with an average value of 5.4 mm/day. The total lake evaporation was estimated to be 975 mm between May and December during the study period. L~~Lake~~ake evaporation between ~~middle~~ January and April is not determined ~~through energy budget method in this study~~ because ~~the energy budget~~part of the lake surface was covered by lake ice during ~~this~~ the study period~~ is can be also affected by intermittent lake ice~~.

>>Fig. 6<<

~~>>Fig. 10<<~~

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~~, $P<0.001$~~), but negatively correlated with net radiation (r^2=0.22~~, $P<0.001$~~), which indicating that the seasonal pattern of lake evaporation is significantly ~~altered~~ 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 ~~to~~ the latent heat flux. When the net radiation was low between ~~November~~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).

~~Significant changes in lake ice phenology occurred at Paiku Co during the study period. Generally, Paiku Co was covered by lake ice between the mid-January and mid-April (e.g. the winter of 2013/2014). During ice-covered period, lake level was very stable because lake ice can effectively prohibit evaporation. However, lake surface of Paiku Co did not completely frozen up between 2015/2016 and 2017/2018 with only intermittent lake ice in the shoreline region. Contrasting with the ice~~

~~covered period, Paiku Co's water level decreased considerably by 199 mm on average between January and April. Assuming lake evaporation between January and April is equal to lake level decrease because there was almost no surface runoff during this period, annual lake evaporation at Paiku Co is estimated to be 1174 mm during the study period. This also indicates that that annual lake evaporation increased by ~20.4% in recent years due to the disappearance of lake ice.~~

~~4~~3.4 Contrasting hydrological and thermal intensities determine seasonal lake level variations~~Impact of lake evaporation on~~Implications for ~~the seasonal lake level variations on the TP~~~~of Paiku Co~~

~~Contrasting hydrological and thermal intensities determine seasonal lake level variations of Paiku Co.~~ ~~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.~~

~~As shown by~~Fig.6a~~ Lei et al (2018),~~ shows~~ ~~ that there is contrasting pattern of hydrological and thermal intensities at Paiku Co. ~~Contrasting hydrological and thermal intensities play an important role in the seasonal lake level variations of Paiku Co. We can find that contrasting hydrological and thermal intensities determine seasonal lake level variations. During the summer monsoon season, w~~P~~ater gain from both p~~recipitation and lake inflow were mainly concentrated during the summer monsoon season (Jul and Aug)~~, and high,~~ ~~mean~~while~~,~~ lake evaporation was ~~still ~~relatively low during this period (Fig. 6b, c), which together le~~a~~ad~~s~~ 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)~~ (Oct. to Dec.)~~, ~~water gain from both p~~precipitation and lake inflow were already very low, ~~mean~~while lake evaporation was in ~~very~~its high value, which le~~a~~ad~~s~~ 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~~ of Paiku Co~~.

Lake evaporation can largely determine the amplitude of lake level changes in dry seasons. Paiku Co's ~~l~~lake level ~~at Paiku Co~~ decreased considerably at a rate of 3.8 mm/day on average during the post-monsoon season (~~between~~ Oct~~ober~~ ~~and~~to Dec~~ember~~), which is in contrast to the slight decreasing rate of 1.3 mm/day ~~in~~during the pre-monsoon season ~~-~~(~~mid-April,~~ ~~and~~~~to~~ May) (Fig.6, Lei et al., 2018). So, what is the main cause ~~for~~of the ~~large~~ differen~~ce of~~t rate of lake level decrease during the two dry seasons? Runoff measurements at the three main rivers feeding Paiku Co indicate that the surface runoff had a weak impact on lake level changes during the~~ pre-monsoon and post-monsoon~~ two dry seasons (Tab. 3). The seasonal pattern of lake evaporation can explain this well. High lake evaporation ~~rates~~ during the post~~-~~-monsoon season led to the rapid lake level decrease, while low lake evaporation ~~in~~during the pre-monsoon season led to much lower lake level decrease. ~~This suggests that lake evaporation can largely determine the amplitude of lake level changes in dry seasons.~~

In a larger sense, ~~our result may have implication for the different patterns of lake level seasonality that have been observed on the TP. Phan et al. (2012) showed that seasonal lake level variations in the southern TP are much larger than those in the northern and western TP.~~ 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 ~~cold~~post-monsoon season (~~October, to December.~~Fig. 7), while lake level at two nearby small lakes, Bam Co and Dawa Co, decreased slightly by 0.1-0.2 m during the same period. Different lake heat storage can play an important role in the amplitude of lake level seasonality. For deep lakes (e.g. Paiku Co, Nam Co and Zhari Namco), the latent heat flux (lake evaporation) over lake surface may lag the solar radiation by several months due to the large heat storage~~ of lake water~~. For this kind of lake, the lake level drop ~~is most dramatic~~mainly occurs ~~in~~during the ~~autumn and early winter~~post-monsoon season when lake evaporation is high but ~~runoff~~lake water input is already very low. For shallow lakes, the latent heat flux closely follows solar radiation, ~~with~~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~~evaporation (mainly through sublimation) ~~is~~can be ~~effectively~~significantly ~~prohibited~~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<<

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4 Discussion

4.~~2~~1 Uncertainty of lake evaporation estimation

In this study, ~~There are several factors that can cause u~~Uncertainty of lake evaporation can be mainly caused by ~~in this study is mainly includes~~the following ~~factors~~~~aspects~~factors, net radiation, meteorological data (air temperature and humidity), lake surface temperature and changes in lake heat storage. The first ~~one~~ factor causing uncertainty of lake evaporation is the determination of solar radiation and atmospheric long wave radiation~~ at Paiku Co~~. ~~In this study, s~~Solar radiation and atmospheric long-wave radiation at Qomolangma station~~, which is about 150 km away from Paiku Co,~~ were used to represent values at Paiku Co. To evaluate the spatial difference, we made a comparison of solar radiation at Paiku Co and Qomolangma Station by using Hamawari-8 satellite data (Tang et al., 2019; Letu et al., 2020). The results show that daily solar radiation at the two sites exhibited very similar seasonal fluctuations (R^2=0.55, P<0.001), with ~~standard deviation~~RMSE of 23.9 W·m^{-2} (9.5% of solar radiation). ~~Assuming approximately 70% of the net radiation was consumed by lake evaporation (Lazhu et al., 2016), the uncertainty of lake evaporation due to error in solar radiation was ~74.5 mm per year (ΔE_1).~~

The second factor ~~that can cause uncertainty of lake evaporation~~ is the uncertainty of meteorological data~~ overlying the lake surface~~. Meteorological data at the shoreline (air temperature and relative humidity) ~~i~~is used to calculate lake evaporation~~ of Paiku Co~~. To check its representativeness, we ~~first~~ made a compari~~e~~son 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~~ (Fig. 11)~~. Results show~~s~~ that both air temperature and relative humidity fluctuated very similarly between the shoreline and lake centre (Fig. ~~7~~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 ~~we evaluate~~ the RMS~~ error~~E of air temperature and ~~humidity~~water vapour pressure ~~the~~ in the shoreline are estimated to be 0.91 °C and 0.069 kPa by using those in the lake centre as true value.

>>Fig. ~~7~~8<<

~~For air temperature, there is average difference of 1 °C between shoreline and lake centre. For water vapor, there is average difference of 1 kPa between shoreline and lake center.~~

The third factor ~~that can cause uncertainty~~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 data. By comparing with MODIS derived nighttime lake surface temperature in 2016 and 2017, we found that there is difference of ~1 °C between the two data, which is used to estimate the uncertainty of lake evaporation~~ 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 °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 °C higher than lake body temperature. Therefore, the difference between lake surface temperature and in-situ observation is estimated to be 0.6 °C for a whole year.

The ~~second~~ fourth factor ~~affecting~~ ~~that can cause the estimation~~~~uncertainty of lake evaporation~~ is the uncertainty of changes in lake heat storage. Changes in lake heat storage are ~~further~~ determined by lake ~~volume~~~~bathymetry~~water storage and lake water temperature profile. Uncertainty of lake water storage mainly results from the measured water depths, interpolation algorithms, volume calculation methods, etc. ~~It is difficult to know the uncertainty because the true lake volume is unknown.~~ The depth sounder measured the water depth at an accuracy of 1%, and the maximum water depth of Paiku Co is 70 m.

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~~Assuming the uncertainty of the water depth is 1 m, the uncertainty of lake volume is estimated to be 2.5%, according to the average water depth of ~40m at Paiku Co.~~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.

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~~According to Qiao et al (2018), error in lake water storage at Bangda Co on the western TP is estimated to be ~10% of the tot~~

Uncertainty of total lake evaporation ~~in this study was~~is ~~also~~ ~~validated~~ estimated by comparing lake level changes during the pre-monsoon and post~~-~~-monsoon ~~season and pre-monsoon~~ seasons when the runoff ~~was~~ is ~~still very~~ low. Runoff measurements at the three large rivers feeding Paiku Co are shown ~~(Fig. 1~~Tab. 3.~~)~~ ~~makes it possible to compare the lake evaporation with lake level decrease.~~ During the pre-monsoon season (~~mid-April to mid-May~~May), lake evaporation (1.7 mm/day) ~~was~~ is ~~quite~~ similar with the ~~decreasing~~ rate of lake level decrease (1.8 mm/day). ~~The high consistency between lake evaporation and lake level decrease confirms the reliability of lake evaporation estimation.~~ During the post-monsoon season (~~October~~ Oct to ~~January~~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~~ (Tab. 3)~~. As shown in Table 3, runoff at the three large rivers can contribute to lake level increase by ~~0.7~1.6~~1.2 mm/day on average in October, thereby partially offsetting lake level changes from lake evaporation. ~~-~~According to ~~this~~ the difference ~~of~~ between lake ~~water input~~evaporation and the sum of ~~output~~lake level decrease and runoff (0.~~9~~ 4 mm/day) ~~during the post-monsoon season~~, the total error of lake evaporation is estimated to be ~~82.8~~96 mm during the ~~whole~~entire ice-free period ~~between~~ (May ~~and~~to Dec~~.~~)~~ember~~~~/year~~.

~~makes it possible to compare the lake evaporation with lake level decrease.The high consistency between lake evaporation and lake level decrease confirms the reliability of lake evaporation estimation.~~

4.~~3~~ 2 Comparison ~~of~~ with ~~lake evaporation with~~ other lakes on the TP

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

To further explore the impact of lake heat storage on the seasonal pattern of lake evaporation, we compared lake evaporation at Paiku Co with other lakes on the TP. We only selected lakes with direct measurements of lake evaporation, including the eddy covariance system or energy budget method. At Ngoring Lake (area, 610 km^2; mean depth, 17 m) on the eastern TP, Li Z. et al. (2015) investigated the lake's energy budget and evaporation in 2011-2012 using the eddy covariance system, and found that the latent heat at Nogring Lake was lowest in June, peaked in August and then decreased gradually from September to November. At Qinghai Lake (area, 4430 km^2; mean depth, 19 m) on the northeast TP, Li X. et al. (2016) conducted studies concerning the lake's energy budget and evaporation in 2013-2015 using the eddy covariance system, and found that there was a 2–3 month delay between the maximum net radiation and maximum heat flux. Compared with Paiku Co ~~the two larger but shallower lakes~~, we can find that there was ~~longer~~ shorter time lag between the heat flux and net radiation at ~~at Paiku Co~~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 ~~the~~ deep lakes like Paiku Co can store more energy in spring and ~~early~~ summer than relatively shallow lakes, and can release more energy to the overlying atmosphere in the ~~autumn and early winter~~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., ~~2016~~2017, 2019). Haginoya et al. (2009) found that lake evaporation at Nam Co was lowest in May and highest in October. ~~The Bowen ratio derived lake~~ Lake evaporation at Nam Co was estimated to be 916~986 ~~-~~mm ~~in 2013 (Lazhu et al. 2016)~~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 ~~pattern of~~variations ~~lake evaporation~~, although ~~lake evaporation~~it ~~at Paiku Co~~ 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 ~~between October and December~~during the post-~~-~~monsoon season can not be further compared because the energy flux at the lake was not measured at Siling Co.

~~4.4 Implications for the seasonal lake level variations on the TP~~

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~~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.~~

~~As shown by Lei et al (2018), lake level at Paiku Co decreased considerably at a rate of 3.8 mm/day on average between October and December, which is in contrast to the slight decreasing rate of 1.3 mm/day in mid-April and May. So, what is the main cause for the large difference of lake level decrease during the two dry seasons? Runoff measurements at the three~~

~~main rivers feeding Paiku Co indicate that the surface runoff had a weak impact on lake level changes during the pre-monsoon and post-monsoon seasons (Tab. 3). The seasonal pattern of lake evaporation can explain this well. High lake evaporation rates during the post monsoon season led to the rapid lake level decrease, while low lake evaporation in pre-monsoon season led to much lower lake level decrease. This suggests that lake evaporation can largely determine the amplitude of lake level changes in dry seasons.~~

~~In a larger sense, our result may have implication for the different patterns of lake level seasonality that have been observed on the TP. Phan et al. (2012) showed that seasonal lake level variations in the southern TP are much larger than those in the northern and western TP. 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 cold season (October to December), 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 of lake water. For this kind of lake, the lake level drop is most dramatic in the autumn and early winter when lake evaporation is high. For shallow lakes, the latent heat flux closely follows solar radiation, with high lake evaporation during the pre-monsoon and monsoon seasons, and low lake evaporation 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 is effectively prohibited. Consequently, lake level decreased more slowly in 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).~~

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~~ at Paiku Co, a deep alpine lake in the central Himalayas~~. The results show that Paiku Co is a dimictic lake with clear lake stratification occurring between July and October. The surface water reached to its highest temperature in late August while the bottom water reached to its highest in two months late (middle to late Oct~~ober~~.). The thermocline formed between 15 m and ~~30~~ 25 m water depth, with the largest temperature difference ~~(~~of 5~6 ^{o}C~~)~~ ~~occurring~~ in late August. ~~The lake is completely mixed between November and June. Considerable spatial difference of lake water temperature was also investigated between the southern and northern basins of Paiku Co.~~

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 ~~about a~~ ~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±~~82~~ 96 mm between May and December ~~during the study period~~, with low values between May and June (1.7 mm/day), and high values between October and December (5.4 mm/day). ~~Our result also indicates that that annual lake evaporation increased by ~20.4% during the study period due to the disappearance of lake ice.~~

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

Data availability

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

Author contribution

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

Competing interests

The authors declare that they have no conflict of interest.

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Figure and Captions

Table 1 The related information about hydro-meteorology observations

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

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

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

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

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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). ~~**The measuring dates of runoff are shown in brackets.**~~

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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

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

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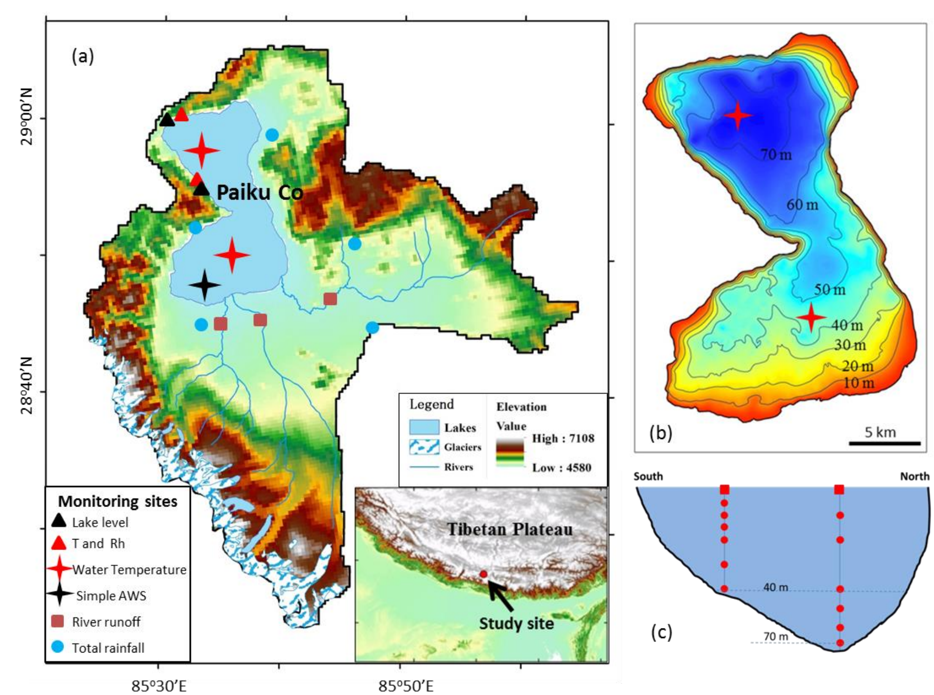

Figure 1: Monitoring sites of lake water budget at Paiku Co basin. (a): Monitoring sites of ~~lake~~ lake level, hydro-meteorology, water temperature profile, runoff, and total rainfall~~ at Paiku Co basin~~. ~~The upper right denotes~~(b): ~~the~~

The isobath of Paiku Co and the two monitoring sites of water temperature profile. (c): ~~The lower right denotes t~~The water temperature monitoring at different water depths.

~~**Figure 2: The monitoring site of air temperature and humidity at the north (A) and central (B) shoreline of Paiku Co.**~~

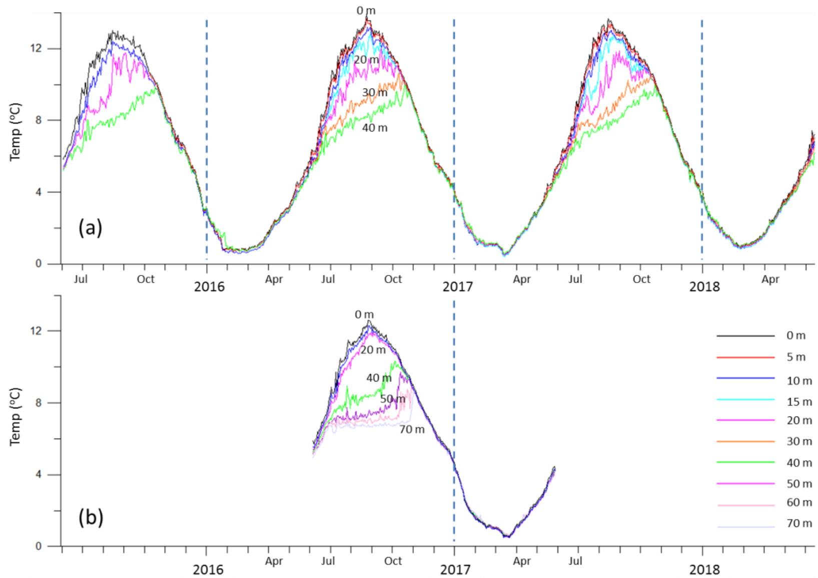

Figure ~~3~~2: Time series of daily lake water temperature at different water depths in Paiku Co's southern (~~A~~a) and northern (~~B~~b) basins.

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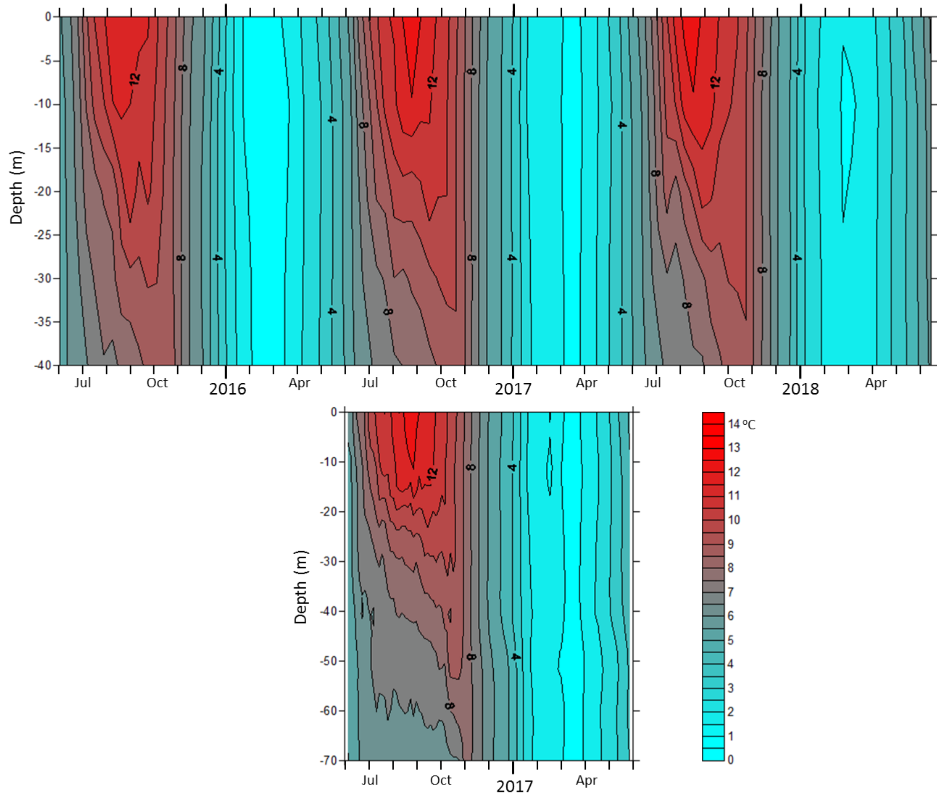


Figure ~~4~~3: Depth-time diagram of isotherm (°C) in Paiku Co's southern (upper, 42 m in depth) and northern (below, 72 m in depth) basins between June 2015 and May 2018.

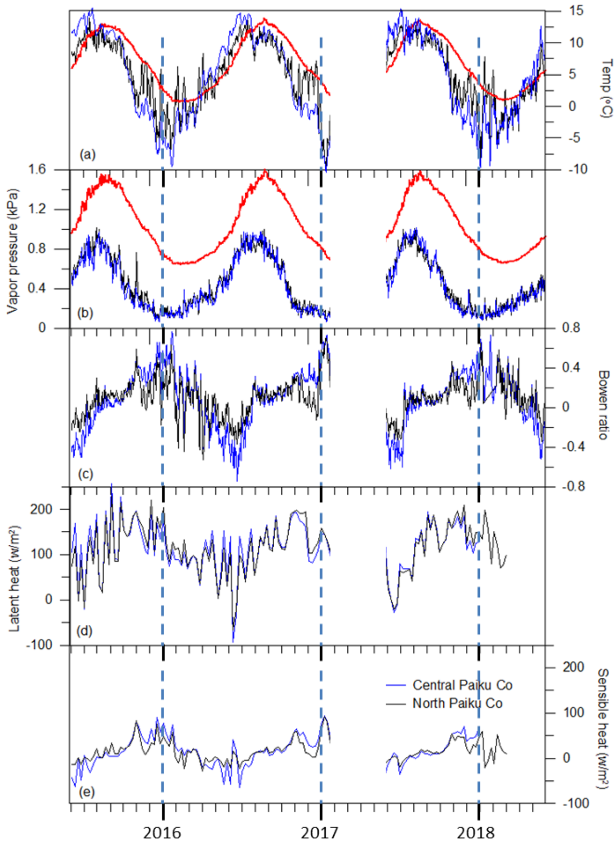
~~**Figure 5: A comparison of water temperature at the depth of 0 m, 10 m, 20 m and 40 m between the southern (black) and northern (red) basins (A-D), and between lake center (black) and shoreline (blue, green E-F).**~~

~~**Figure 6: Time series of hydro-meteorology at the north (blue lines) and central (red lines) shoreline of Paiku Co. A: Daily surface water temperature (black), atmosphere temperature, and their differences. B: Actual vapor pressure at lake surface (black) and the overlying atmosphere (blue), and their differences.**~~

Figure ~~7~~4: ~~Time series of~~ The main components of energy budget at the lake surface and changes in lake heat storage. ~~(daily solar radiation (A~~a)~~),~~ : Downward short wave radiation, (b): ~~a~~Atmospheric long wave radiation to lake ~~(B)~~, (c): ~~l~~Long wave radiation emitted from lake ~~(C) and~~, (d): ~~n~~Net radiation, ~~(D)~~ (e): Weekly changes in lake heat storage (G). ~~atmospheric long wave radiation to lake (B), long wave radiation emitted from lake (C) and net radiation (D) over Paiku Co.~~

~~Figure 8: Time series of weekly net radiation, changes in lake heat storage (A) at Paiku Co, and heat flux at the lake surface (B).~~

~~Figure 9: Time series of Bowen ratio (A), weekly latent (B) and sensible (C) heat flux at the north (black) and central (red) shoreline of Paiku Co.~~



1385 **Figure 5: Hydrometeorology and heat flux at the lake surface. (a): Air temperature and daily surface water temperature (red line), (b): Actual vapour pressure at lake surface (red line) and the overlying atmosphere, (c): Bowen ratio, (d-e):Weekly latent and sensible heat flux at the lake surface. For a-e, black lines denote north Paiku Co and blue lines denote central Paiku Co.**

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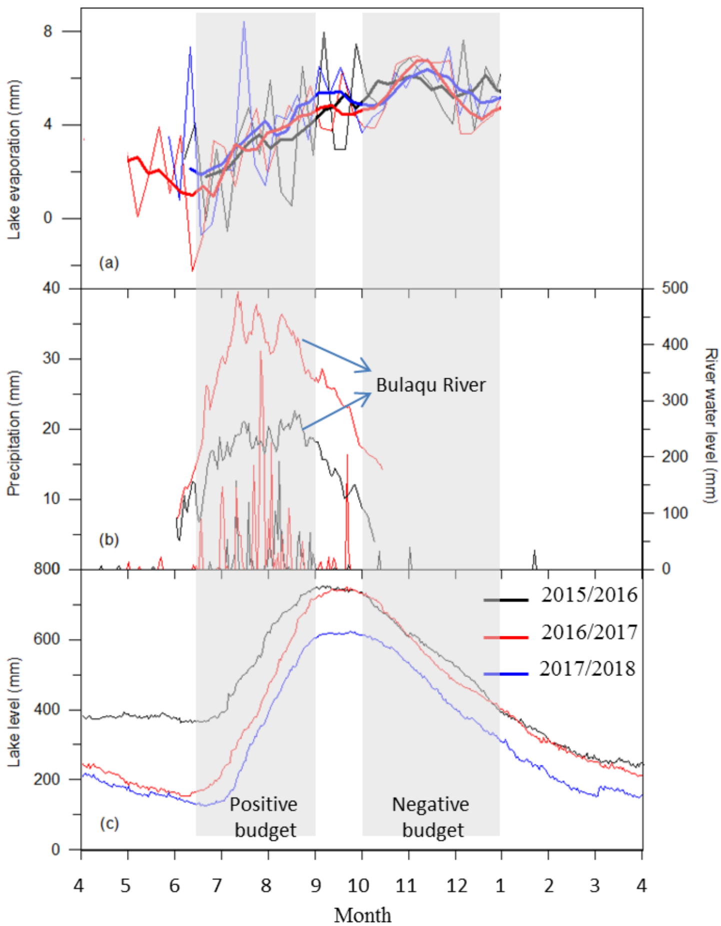

Figure ~~10~~6: The main components of lake water budget at Paiku Co. (a): Weekly lake evaporation derived from the north shoreline of Paiku Co. ~~Seasonal lake level variations.Time series of wWeekly lake evaporation at Paiku Co derived from the north shoreline of Paiku Co.~~ (b): Precipitation at Qomolangma station and water level of Bulaqu River in 2015 and 2016. ~~Weekly lake evaporation at Paiku Co derived from the north shoreline of Paiku Co.(A) and Seasonal lake level variations(B) at Paiku Co between June 2015 and May 2018.~~ (c): Seasonal lake level variations of Paiku Co. The thick lines (~~A~~a) denote the 5-point running average. ~~Lake evaporation derived from the north (black) and central (red) shoreline of Paiku Co are compared.~~ Grey rectangles represent positive and negative lake water budgets in monsoon and post-monsoon seasons, respectively.

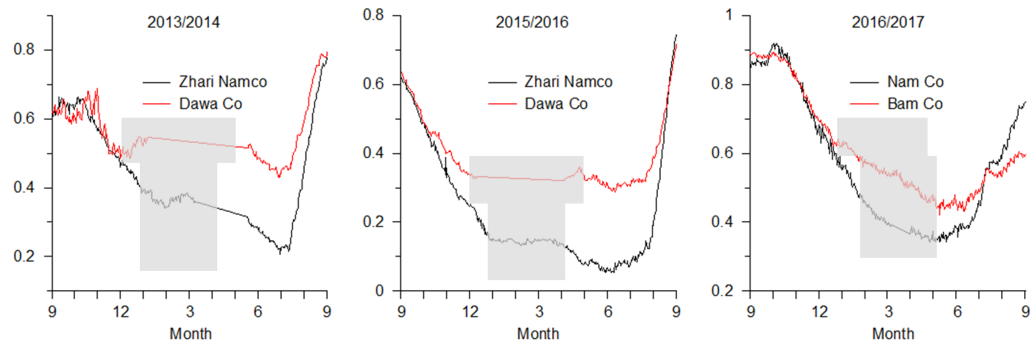

Figure 7: Different amplitude of seasonal lake level changes between deep and shallow lakes on the central TP. Relatively deep lakes: Zhari Namco (85.61 ^{o}E, 30.93 ^{o}N) and Nam Co (90.60 ^{o}E, 30.74 ^{o}N); Relatively shallow lakes: Dawa Co (84.96 ^{o}E, 31.24 ^{o}N) and Bam Co (90.58 ^{o}E, 31.26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

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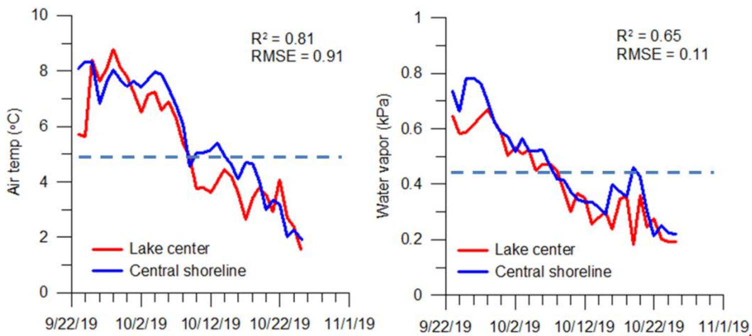

Figure ~~11~~8: A comparison of air temperature and ~~relative humidity~~water vapour pressure between shoreline and lake centre.

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