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Discussions

Interactive comment on "Thermal regime, energy budget and lake evaporation at Paiku Co, a deep alpine lake in the central Himalayas" *by* Yanbin Lei et al.

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General comments

Reply: Thanks a lot for the constructive and detailed comments about our submission. They are important for further improving the manuscript. We will consider these comments and revise the manuscript carefully. A general reply to your comments has been made as the following:

About the uncertainty of lake evaporation

Reply: We will evaluate the uncertainty of lake evaporation at Paiku Co in the following

aspects, net radiation, lake meteorological data (air temperature and humidity) in the shoreline, surface water temperature, and changes in lake heat storage. Uncertainty of net radiation has been evaluated in the submission. Uncertainty of air temperature and humidity, lake surface temperature, changes in lake heat storage will be evaluated in the revision. The error of air temperature and humidity the in the shoreline will evaluated by comparing with those in the lake center. We set up a platform at the water depth of ∼19 m in southern Paiku Co in September 2019, and we only acquired one month's hydro-meteorological data from 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 with correlation coefficient of 0.9 (R2=0.81), indicating that meteorological data in the shoreline can be used to calculate lake evaporation. RMS error of air temperature is estimated to 0.91 oC between center and shoreline during the observing period (23 September to 25 October 2019). RMS error of air temperature is estimated to 0.069 kPa between shoreline and center. For lake water temperature, 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. In order 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. MODIS lake surface temperature is usually 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. In spring and summer when the lake water gets warm, the skin temperature derived from MODIS data is about 1.2 oC higher than lake body temperature. In spring and winter when the lake water gets cool, the skin temperature derived from MODIS data is about only 0.05 oC higher than lake body temperature. Therefore, the difference of 0.6 oC between MODIS LST and in-situ observation data during a whole year is used to estimate the uncertainty of lake evaporation in the revision. Uncertainty in lake heat storage is mainly determined by errors in lake water storage and lake water temperature profile. 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 $\sim$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. Lake water temperature profile was measured by HOBO logger at an interval of 5-10 m with an accuracy of $\pm$0.2 oC. The spatial difference of lake water temperature is investigated by comparing water temperature profile at the northern and southern centers of Paiku Co. The error of lake evaporation caused by lake water temperature difference on the northern and southern centers of Paiku Co is estimated to 35 mm.

Introduction. - The originality of the study:

Reply: 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 still unclear. 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.

- 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 will address 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. Uncertainty of air temperature and humidity has been evaluated (please see reply above)

- 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 will be discussed in the revision.

- 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 G in this study because there is no data available about G.

- 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.

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

Reply: What we want to address is that lake heat storage in summer is mainly determined by water temperature changes in the upper layer because the lake water is stratified, but in other seasons, the lake is fully mixed, lake heat storage is determined not only by the upper water, but also the bottom layer.

- 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: As far as my knowledge, water convection is weaker when the vertical temperature gradient is larger because of its high stability. 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: Please note that 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: Generally, lake water temperature at the lake center can stand for the average thermal condition, but lake water temperature at the shoreline is more regional.

- 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 will address this paragraph in more detail. We do not determine lake evaporation between middle 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. So we gave a rough estimation according to lake level change during this period when there is almost no river discharge and little precipitation.

- 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 will mention it in the revision.

- 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 suggestion. We will give uncertainty of lake level variations in winter season between 2013 and 2019.

- 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: Thanks for the good suggestion. We will calculate the uncertainty according to estimation at Paiku Co in this study.

- 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. We will give uncertainty of lake evaporation in winter season. Error of lake level changes will be estimated and taken as uncertainty of lake evaporation 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: Changes in lake heat storage at Paiku Co are quantified and its impact on seasonal changes in lake evaporation is addressed in this study. 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. We will further summarize the new findings in the revision.

- 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: Beside lakes on the TP, we will check the water level changes of endorheic lakes in other regions of the world, and further compare them with 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 will clarify 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.

Below are my comments made to the authors' reply of the previous version. Since many of the points were not reflected in the current version, I cite them again here.

A. About the representativeness of meteorological data

Reply: We have added the meteorological data in the lake center and further compared these data with those in the shoreline. We agree that hydro-meteorological data at the shoreline does not completely satisfy the standard of Bowen ratio calculation, but at present it is difficult to install platform in the center in such a deep lake. We set up a platform at the water depth of $\sim$19 m in southern Paiku Co in September 2019, and had attempted to get real hydro-meteorological data in the lake center. Unfortunately the platform was destroyed by lake ice and AWS station was lost in winter 2019. We

only acquired one month's hydro-meteorological data from the lake surface. After comparison, we found air temperature and humidity in the lake center varied similarly with those at the shoreline.

B - They are an estimation based on sensor specifications. What happened to the radiation effect on the measurements?

Reply: The instrument was installed just under a big stole where there is good ventilation. Radiation can not affect the equipment.

C 4. L103-106. About lake surface water temperature. Please show the data to validate this statement.

Reply: Please see the reply to the major comments. In situ measurement has validated by MODIS lake surface temperature data.

F 13. L333-335. About In-situ observations of runoff at the three main rivers. Perhaps the authors' reply is an indirect manner, but and I do not understand the logic of the authors' reply.

Reply: I think our reply is already very clear. 'Besides runoff measurement in the three rivers, water level is also records by using HOBO water level loggers. We found that this discharge can approximately represent the average state in spring and autumn. Fieldwork in early April 2018 shows that there was almost no surface runoff between January and March.'

Specific comments: 1. Bowen ratio As I mentioned above, the authors' reply has not convinced me that their measurements can be used to estimate the Bowen ratio above the lake. Since it appears that they do not have evidence that their temperature and humidity measurements are equivalent to those over the lake, what I could suggest is to stop using the name of the "Bowen ratio method". Instead, they could introduce a new method (or a new name), a kind of empirical Bowen ratio method, or a relaxed version of the Bowen ratio method. In this method, a new variable Bo' is defined similarly to the

Bowen ratio Bo but air temperature and humidity over the lake surface are replaced with that those over the land surface. Ideally, the validity of this empirical method should be studied first with an independent method. But alternatively, authors could do it indirectly through the comparison of evaporation with water level decrease as they have done in their study. The only difference is whether they refer their method as the Bowen ratio method or not; I simply do not think it is appropriate to call it Bowen ratio based on their measurement. By the way, this type of empirical methods have been proposed and applied to lake evaporation estimation. For example, Harbeck (1962)'s empirical mass transfer formula for evaporation is E=N u (es-ea). N is the mass transfer coefficient, u is wind speed, es is at the water surface, but ea is over the land surface.

Reply: About the hydro-meteorological data used in this study, we agree that it does not completely satisfy the standard of Bowen ratio calculation. We will evaluate the uncertainty of all the data used in this study and found the data we used in this study is generally suitable to study lake energy budget, evaporation and its impact on seasonal lake level changes.

Besides lake evaporation, our study investigates the thermal regime and energy budget of Paiku Co. We give a detailed description of changes in lake heat storage through in situ measurement of water temperature profile and energy budget at Paiku Co is investigated accordingly. As far as my knowledge, this is the first time to give such a detailed investigation of energy budget on the TP. Although the reviewer does not agree that energy budget is not a direct method to investigate lake evaporation, eddy covariance method can exactly not know the changes in lake heat storage of the whole lake and its impact on the seasonal pattern of lake evaporation.

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