Responses to the comments from the Referee #1

We are very grateful to the Referee for the comments on our manuscript. Those comments are all valuable and very helpful for revising and improving our manuscript. We have substantially revised our manuscript after reading the comments. The Referee's comments are shown in bold and our responses immediately follow.

The paper is focused on Qinghai Lake, the largest of thousands of lakes situated on Tibetan Plateau, China. The lake is brackish with salinity about 12.5 g/L. The authors use the well-known one-dimensional model FLAKE forced with a local set of historical gridded meteorological data for the period 1979-2012 to simulate the thermal and ice regimes and their ongoing trends accompanying the global warming. Because the Qinghai, as well as all other Tibetan lakes, has been very sparsely covered by in situ measurements, and virtually no field monitoring data are available (except those from a single meteorological buoy used in this study), numerical simulation is the only mean capable of giving quantitative insights into the long-term variability of the Tibetan lakes. Therefore, in my opinion, the article presents interesting and useful information and should be published after moderate revision.

Comment #1：

My only general comment about this manuscript is as follows: I think that the possible role of salinity and its changes in the estimated long-term variability of the lake regime should be evaluated and discussed more thoroughly. For instance, can the trends of the ice regime (section 3.3) be associated not only with the air temperature increase, but also, at least partly, with salinity increase over the period 1961-2004? According to the information supplied in section 2.1, the lake level dropped for about 3.3 m during this period, which, given the mean depth of 21 m and mean salinity about 10 g/L, implies salinity increase of about 2 g/L. This, in turn, may have affected the ice regime.

Generally, salinity may exercise influence on the issues addressed in the article through (1) salinity stratification, which is not accounted for in the FLAKE model, but may strongly affect vertical mixing; (2) temperature of maximum density, which is different from that of fresh water and may affect winter convection; and (3) freezing temperature, which is different from that of fresh water and may affect the onset and duration of the ice cover period. While the first of these mechanisms is difficult to be included in the model designed for freshwater lakes, the other two, probably, could be taken into account, if it is possible to replace the respective constants in the model (i.e., the freezing temperature and the maximum density temperature) by those appropriate for Qinghai Lake. I suspect that the exact values of either variable for the Qinghai are unknown because of the lack of direct measurements and because the ionic composition of the lake is different from that of the ocean. However, as a "first guess", the oceanic values for the respective salinity 12.5 g/L can be considered - namely, about -0.65 °C for freezing point, and about 1.6 °C for TMD. If it is possible to repeat some of the experiments done using FLAKE with the settings modified accordingly, and then assess the differences in the outcomes of the "freshwater" and "salty" experiments, this would allow to evaluate the role of salinity vs air temperature and surface fluxes and hence strengthen the study. If this approach is technically not possible, potential role of salinity still should be discussed in the paper, perhaps based on literature and data from other similar lakes.

Author's response: Thanks for the good evaluation and kind suggestions. We agree with the Reviewer that the salinity effects deserve an extended discussion. The influence of salinity changes over the period 1961-2004 on ice regime trend can indeed be hypothesized. However, quantification of the salinity effect and its comparison with the air temperature influence needs a separate in-depth study. First, specific changes in the salinity of Qinghai Lake require a stronger data support than an approximate estimation from lake depth changes. However, at present, we do not have historical data on the change of salinity in Qinghai Lake. Second, apart from air temperature and salinity, the ice regime is also influenced by other factors, such as wind, water circulation under ice cover and precipitation, which should be taken in to account, but are not considered in the framework of 1-D modeling. Hence, the effect of changes in salinity on lake ice regime cannot be clearly distinguished from other factors by using FLake model with a simple salinity parameterization. Last, the simulated ice durations were shortened 21.1 days and 26.6 days during 26 years from 1979 to 2004 for the freshwater and salt water simulations respectively. After considering the 12.5 g/l salinity effects on temperature of maximum density and freezing point, the average ice duration reduced ~13.8 days (Fig. 7 in revised manuscript, already enclosed). When the salinity changes ~1.2 g/l from 1979 to 2004 (correspond to 2g/l from 1961 to 2004), the ice duration may approximately reduce ~1.3 days, which is much small than 26.6 days caused by meteorological factors. The influence of lake level caused salinity change on ice duration can be ignored compare to meteorological factors here. Hence, we considered the salinity effects but ignored its variation in the study, and focused on the lake response to the meteorological forcing. In reply to this useful comment, we added these considerations to the discussion (see the changes in the manuscript below) and will consider it in future research.

Just like what the referee said and we mentioned above, the mechanism of salinity stratification is difficult to be included in the model designed for freshwater lakes and the vertical salinity gradient of the lake was scarcely observed. We agreed with the Reviewer's suggestion and parameterized the salinity effects on the temperature of maximum density (T_m) and freezing point (T_f) into the lake model based on linear approximations of empirical function of state of seawater, then rerun the Flake model. With the consideration of salinity effects, the lake ice phenology had been improved. Correspondingly, the simulation results were changed respectively, and the relevant parts of the manuscript were revised. The major quantitative conclusions of the study remained unchanged.

The mainly relevant parts in the manuscript were also revised as follows:

(1) In section 2.3 Lake model, the parameterizations of salinity effects were added:

"Considering that we are applying a freshwater lake model to a brackish lake, the equation of state used by FLake was adjusted by changing temperature of maximum water density (T_m) and freezing temperature (T_f). The T_m and T_f formula obtained from linear approximations of empirical function of state of seawater (Caldwell, 1978; UNESCO, 1981) are:

$$\mathrm{T_m}[°\mathrm{C}] = 3.98\text{-}0.216S \qquad (5)$$

$$T_f[°\mathrm{C}] = -0.055S \qquad (6)$$

Where the S is salinity taken in parts per thousand (‰ or $g \cdot L^{-1}$). For the salinity of S=12.5g/L, which is the case of Qinghai Lake, the equation gives $T_m = 1.28°C$ and $T_f = -0.69°C$."

(2) In section 3.3 Lake ice cover, the following are added:

“The salinity parameterization for temperature of maximum density and freezing point had a certain effect on the ice phenology simulated by FLake (Fig. 7 in revised manuscript, enclosed). The maximum ice thickness was reduced compared with default (freshwater) model setting. The freeze-up data was delayed and the break-up data was advanced, leading to a shorter ice duration period. Nevertheless, the interannual changes between them remained consistent and the break-up date and ice duration period are closer to observation.”

(3) In part 4.1 Model performance, the following are added:

“Salinity can influence the temperature of maximum density (T_m) and the freezing temperature of water (T_f). According to the 12.5g/L salinity of Qinghai Lake, these two parameters equal to 1.28 °C and -0.69 °C instead of the default model configurations of 4 °C and 0 °C respectively. Considerations of the salinity effects lead to a slightly earlier of the spring overturn and a later autumn overturn and consequently to an extension of the lake stratification period. Because the salinity stratification effects cannot be completely included in the model designed for freshwater lakes, the simulated mixing regime may have some differences from the actual situation of Qinghai Lake. The major features of the dimictic seasonal mixing regime, as simulated by the model, may be suggested to be close to the reality.”

(4) And the following are also added in part 4.1:

“Despite a salinity parameterization, the ice phenology modelled by FLake differs significantly from the remote sensing observations. The discrepancy may be related to a number of factors not included in the model. One of them is the effect of salinity on the ice structure, density, and porosity; the others are precipitation, inflows, circulation under ice cover and wind, which is especially important of large-area lakes, like Qinghai Lake (Kirillin et al. 2012). However, the air temperature apparently has the strongest effect on ice regime, especially in long-term changes, which appear to be well-simulated by FLake allowing us to study the effect of air temperature on lake ice regime within the model ability.”

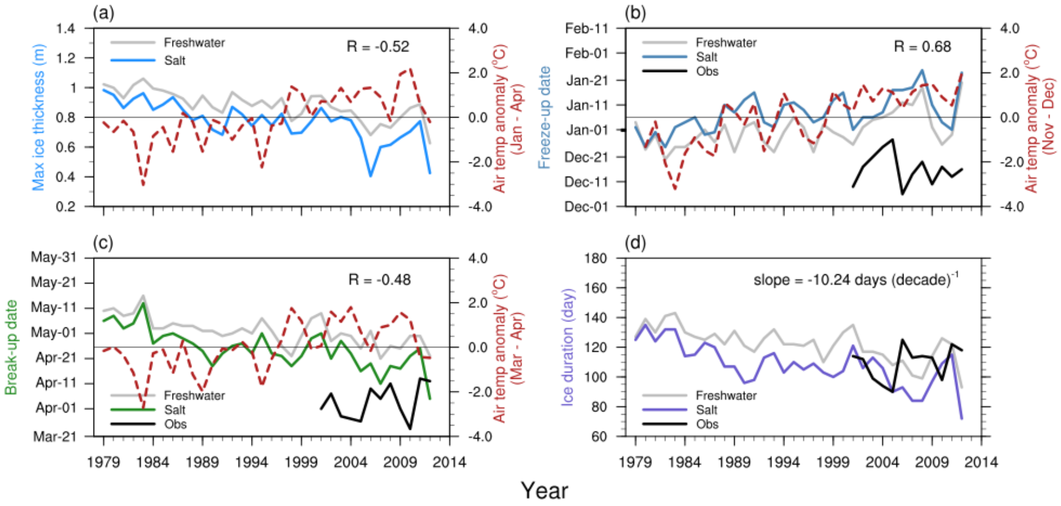

Figure 7: The interannual variations of simulated maximum annual ice thickness (a), break-up date (b), freeze-up date (c) and ice duration period (d) of Qinghai Lake. The coloured (grey) line indicate with (without) salinity parameterization. The red dash line is air temperature anomaly in the specified period and the black line is observed ice phenology derived from satellite.

More specific comments:

Comment #1

The “Study area” Section: The elevation of the Tibetan Plateau is never mentioned in the paper. What is the absolute elevation of Qinghai Lake surface? This is an important piece of information, please specify.

Author's response: The elevation of the Qinghai Lake surface already given in brackets of the first sentence in “study area” section. Maybe it is not very obvious in brackets, so I replaced it with a sentence to specify the elevation of Qinghai Lake. In the revised manuscript, the sentence in “study area” section was changed to:

“It is an endorheic, brackish lake (salinity 12.5 g·L^{-1}, pH 9.3) (Deng et al., 2010) located on the northeast margin of the TP (Fig. 1) at the height of about 3194 m a.s.l.”

Comment #2

P3 Lines 25-30: It follows from these numbers that the lake’s water budget has been shifting towards an increase of the incoming components since 1970, accompanied by the decrease of evaporation. Then why the lake kept shrinking until 2004? Was the rate of shrinking in the 1960s much higher than in the early 2000s? Please explain.

Author's response: The change in lake water level depends on the balance between incoming components and evaporation loss. Many studies on the water level changes in Qinghai Lake show that the water level in Qinghai Lake was declining in fluctuations from 1959 to 2004 (e.g. Zhang et al.,2011; Li et al., 2007; Tang et al., 2018; all cited in manuscript). This is because the water loss (i.e. evaporation) is generally larger than incoming water (e.g. runoff and precipitation) in this period, although the incoming components is increasing and the evaporation is decreasing (Tang et al., 2018), it still need some time to get balance with the water loss, so the lake kept shrinking until 2004 when the increasing incoming water balanced with the water loss. The rate of shrinking of Qinghai Lake in the early of 1960s indeed seems much higher than in the early 2000s (Zhang et al.,2011), but it turned to a temporary expandation in the late of 1960s (e.g. Zhang et al., 2011; Li et al., 2007). We have revised the last paragraph of section 2.1 in manuscript to explain the reason (Page 3 Line 26-32):

"Qinghai Lake is sensitive to climate change. Because the evaporation is generally larger than river runoff and precipitation, the water level of Qinghai Lake decreased at the average rate of 7.6 cm per year from 1961 to 2004 (Cui et al., 2016). However, the precipitation continuously increased in 1970-2015 by 15.603 mm per decade according to the data from Gangcha station (the nearest meteorological station approximately 13 km north to Qinghai Lake), and the runoff from the melting of Qilian Mountain glaciers is also increasing because of an increasing temperature of 0.3 °C per decade from 1961 to 2012 in Qinghai lake basin, coupled with the decreasing evaporation by 1.343 mm per year (observed by Gangcha station) during 1970-2003 (Tang et al., 2018). Since 2004, as the runoff and precipitation begin to exceed evaporation, the Qinghai lake stopped shrinking and began to expand, lake level increased at a rate of 14 cm per year during the period 2004-2012. The regional climate gradually turned to the direction of "warm and humid" (Dong and Song, 2011; Zhang et al., 2011, 2014b; Cui et al., 2016)."

Comment #3

P4 L15: "rare abnormal values influenced probably by cloud cover" – if you are confident that these abnormal values are artifacts corresponding to low clouds, then why keep them? Just remove them from your data base and the plot.

Author's response: We have removed the abnormal values according to the referee's comment. And the relevant sentence in the manuscript is changed as follows:

"We have removed few abnormal values that maybe influenced by cloud cover (Langer et al., 2010)."

Comment #4

P5 Section 2.2: More details about the FLake model would be useful. What is the form of the expression for the profile in the lower layer?

Author's response: We are very sorry for the negligence of details about FLake. According to Referee's comment, we added the expression in FLake for the temperature profile in the lower layer in the "2.3 lake model" section of revised manuscript as follows:

"The parameterization formula is:

$$\frac{\theta_s(t)-\theta(z,t)}{\Delta\theta(t)} = \Phi_\theta(\zeta) \quad h(t) \le z \le D \tag{1}$$

Where t is time, z is the depth, $\theta_s(t)$ is the temperature of upper mixed layer of depth $h(t)$, which is computed based on the convective entrainment or relaxation-type equation in terms of wind mixing (Mironov, 2008). $\Delta\theta(t) = \theta_s(t) - \theta_b(t)$ is the temperature differences across the thermocline with the depth of $\Delta h(t) = D - h(t)$, D is the lake depth, $\theta_b(t)$ is the temperature at the bottom of the thermocline. $\Phi_\theta(\zeta)$ is a dimensionless "universal" function of the dimensionless depth $\zeta=\frac{z-h(t)}{\Delta h(t)}$ which satisfies the boundary conditions $\Phi_\theta(0) = 0$ and $\Phi_\theta(1) = 1$. Based on the above theory, the temperature profile parameterization of the two-layer at time t can be obtained:

$$\theta(t) = \begin{cases} \theta_s(t) & 0 \le z \le h(t) \\ \theta_s(t) - [\theta_s(t) - \theta_b(t))\Phi_\theta(\zeta)] & h(t) \le z \le D \end{cases} \tag{2}$$

The shape function $\Phi_\theta(\zeta)$ is calculated by:

$$\Phi_\theta = \left(\frac{40}{3}C_\theta - \frac{20}{3}\right)\zeta + (18 - 30C_\theta)\zeta^2 + (20C_\theta - 12)\zeta^3 + (\frac{5}{3} - \frac{10}{3}C_\theta)\zeta^4 \tag{3}$$

The shape factor C_θ can be computed by:

$$\frac{dC_\theta}{dt} = sign\left(\frac{dh(t)}{dt}\right)\frac{C_\theta^{max} - C_\theta^{min}}{t_{rc}} \qquad C_\theta^{min} \le C_\theta \le C_\theta^{max} \tag{4}$$

Where t_{rc} is the relaxation time scale (s) which is the time of the evolution of the temperature profile in the thermocline from one limiting curve to the other, and sign is the signum function, following the change of sign in $\frac{dh(t)}{dt}$. $C_\theta^{min} = 0.5$ and $C_\theta^{max} = 0.8$ are the minimum and maximum values of the shape factor."

Comment #5

P5 L30 and thereafter: The adjustments introduced to the air temperature and wind speed through linear regressions seem to help very little in minimizing biases between the simulated and the observed LST, so what is the point of using them?

Author's response: The buoy observation data available for bias correction were unfortunately not complete, covering only summer and autumn and some of the data are missing. No correction was performed for other parts of the year; therefore an appreciable bias remained in the results. In addition, the revised air temperature and wind speed may not have enough consistency to use, but it helps in understanding and evaluating the bias caused by the forcing data. We revised the sentence in section 3.1:

"Through the correction of the driving data, we found that positive bias between simulated LST and satellite data can be partly explained by the differences in the forcing weather data measured over the lake and provided by the ITPCAS data, while the remaining bias may be partly attributed to the cool skin effect in the LST sensed by MODIS."

Comment #6

L11 P15: "Keeping in mind the cool skin effect, we can suggest that the model predictions of the bulk LST are even better than the satellite data suggest" – But your Figure 2 shows good agreement between the satellite and the buoy data, and the latter measured bulk temperature. Therefore, it looks like the skin effect in this case did not affect much the satellite-derived temperatures.

Author's response: The satellite observed LST have a little negative bias (-0.36 °C, in summer and autumn) compared with the buoy bulk temperature. While the y-scale of Fig. 2 do not allow to see the bias clearly, the bias values are added to the panels on the figure. If the skin effect, in this case, did not affect much the satellite-derived temperatures, it probably caused by the different measurement methods between satellite and buoy. We have rewritten this part according to the referee's comment and removed the sentence:

“Keeping in mind the cool skin effect,” and add the sentence “Meanwhile, the difference of the measurement method between satellite and buoy may also play a part in it (Leppäranta and Lewis, 2007).”

Other changes:

We tried our best to improve the manuscript and made some changes in the manuscript. These changes will not influence the content and framework of the paper. Many errors in grammar and expression have been revised but not list here. The manuscript will be further revised by the English editorial company.

References:

Caldwell, D., R.: The maximum density points of pure and saline water, Deep Sea Res.,25, 175–181, doi: 10.1016/0146-6291(78)90005-x,1978.

Cui, B. L. and Li, X. Y.: The impact of climate changes on water level of Qinghai Lake in China over the past 50 years, Hydrol. Res., 47, 532–542, doi:10.2166/nh.2015.237, 2016.

Deng, S., Dong, H., Lv, G., Jiang, H., Yu, B., and Bishop, M. E.: Microbial dolomite precipitation using sulfate reducing and halophilic bacteria: Results from Qinghai Lake, Tibetan Plateau, NW China, Chem. Geol., 278, 151–159, doi:10.1016/j.chemgeo.2010.09.008, 2010.

Dong, H. and Song, Y.: Shrinkage history of Lake Qinghai and causes during the last 52 years, 2011 International Symposium on Water Resource and Environmental Protection (ISWREP), Xi’an, China, 20-22 May 2011, 446–449, 2011.

Kirillin, G., Leppäranta, M., Terzhevik, A., Granin, N.,Bernhardt, J., Engelhardt, C,. Efremova, T., Golosov, S., Palshin, N., Sherstyankin, P., Zdorovennova, G., and Zdorovennov, R.: Physics of seasonally ice-covered lakes: a review, Aquat. Sci., 2012, 74, 659-682, 2012.

Langer, M., Westermann, S., Boike, J.: Spatial and temporal variations of summer surface temperatures of wet polygonal tundra in Siberia-implications for MODIS LST based permafrost monitoring, Remote Sens. Environ., 114, 2059–2069, doi:10.1016/j.rse.2010.04.012, 2010.

Leppäranta, M., Lewis, J. E.: Observations of ice surface temperature and thickness in the Baltic Sea, Int. J. Remote Sens., 28, 3963–3977, doi:10.1080/01431160601075616, 2007.

Tang, L., Duan, X., Kong, F., Zhang, F., Zheng, Y., Li, Z., Mei, Y., Zhao, Y., and Hu, S.: Influences of climate change on area variation of Qinghai Lake on Qinghai-Tibetan Plateau since 1980s, Sci. Rep., 8, 7331, doi:10.1038/s41598-018-25683-3, 2018.

UNESCO, The Practical Salinity Scale 1978 and the International Equation of State of Seawater 1980. Technical Paper in Marine Science, 36,1981.

Zhang, G., Xie, H., Kang, S., Yi, D., and Ackley, S. F.: Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003–2009), Remote. Sens. Environ., 115, 1733–1742, doi:10.1016/j.rse.2011.03.005, 2011.

Zhang, G., Yao, T., Xie, H., Zhang, K., and Zhu, F.: Lakes' state and abundance across the Tibetan Plateau, Sci. Bull. (Beijing), 59, 3010–3021, doi:10.1007/s11434-014-0258-x, 2014b.