Reply to RC1

We are thankful to the Reviewers for careful reading of the manuscript and helpful comments and suggestions on the study. Both Reviewers presented similar critical points, which we agreed with and followed in the revision of the study. Therefore, we preface the detailed responses with a general description of the main revision points, reflecting the aims of the study, its novelty, and the major results.

Note: the **comments** and **authors' replies** are in font colors of **black** and **blue**, respectively. The **blue content in quotation marks** is the expression marked in red in the revised manuscript. Figure 2 and Figure 3 merged and Figures 4-8 becomes Figure 3-7 in the revised manuscript.

General response:

1. The revised abstract is focused now on the study background, goals, design, and outcomes:

   "The seasonal ice cover in lakes of the Qinghai-Tibet Plateau is a transient and vulnerable part of the cryosphere, whose characteristics depend on the regional climate: strong solar radiation in the context of the dry and cold environment. We use the first under-ice temperature observations from the largest Tibetan freshwater lake Ngoring and a one-dimensional lake model to quantify the mechanism of solar thermal accumulation under ice, which relies on the ice optical properties and weather conditions, as well as the effect of the accumulated heat on the land-atmosphere heat exchange after the ice break-up. The model was able to realistically simulate the feature of Ngoring Lake thermal regime: the "summer-like" temperature stratification with temperatures exceeding the maximum density point of 3.98 °C across the bulk of the water column. A series of sensitivity experiments revealed solar radiation was the major source of under-ice warming and demonstrated the warming phenomenon was high sensitivity to the optical properties of ice. The heat accumulated under ice contributed to the heat release from the lake to the atmosphere for 1-2 months after ice-off, increasing the upward sensible and latent surface heat fluxes by ~50 W m^{-2} and ~80 W m^{-2}, respectively. Therefore, the delayed effect of heat release on the land-atmosphere interaction requires an adequate representation in regional climate modeling of the Qinghai-

Tibet Plateau and other lake-rich alpine areas."

2. We have deeply revised Introduction and Discussion/Conclusion to better outline the study's aims and its major outcomes. In particular, we state in Introduction that:

   "we adopt for this study a "classical" two-equation turbulence modeling approach proving its reliability in decades of studies on the environmental turbulent fluid dynamics. The one-dimensional model LAKE implements the approach in application to lake dynamics and was applied previously to different lakes (Stepanenko et al., 2011, 2016; Guseva et al., 2016). We combine modeling with in situ observations from Ngoring Lake, data on weather forcing and remote sensing to: (i) test the ability of a one-dimensional lake model LAKE to simulate temperature and stratification driven by intense solar heating in ice-covered Lake Ngoring; (ii) conduct series of sensitivity experiments aimed at revealing the role of meteorological forcing and ice optical properties in lake temperature and mixing regime; and (iii) reveal the effects of temperature distribution before ice breakup on lake heat storage and lake- atmosphere heat transfer."

3. As one of the major novel outputs of the study, we mention in Conclusions:

   "An important consequence of the under-ice solar heat accumulation consisted in increased sensible and latent heat releases in the subsequent open-water phase. According to the model results, the effects on the surface fluxes of Ngoring Lake lasted for 59-97 days after the ice melt and increased the upward latent and sensible surface heat fluxes up to ~80 W m^{-2} and ~50 W m^{-2}, respectively. Herewith, the phenomenon of under-ice solar heating may have a significant effect on the land-atmosphere interaction on regional scales and has to be accounted for in coupled climate models."

4. In the revised study, we focus on the major factors affecting the penetration of solar radiation under lake ice, and later heat release from the water column to the atmosphere after the ice melt.

We hope that these changes have resolved the conceptual issues raised by the Reviewers and provided the study with the right context. Detailed responses and descriptions of changes are given below.

- I think this paper is trying to understand how solar radiation influences thermal stratification under lake ice on a large lake on the Tibetan Plateau. This is an admirable goal, but it isn't clear what the novelty of this paper is. I would say aspects of this process are well known, and hence introduction needs to better review existing literature and make it clearer what new contribution in this work. I would say it is well known that over winter lakes warm up under ice. This is a key point in the highly cited 2012 review by Kirillin (Who is one of the co-authors on this paper!)

Kirillin, Georgiy, Matti Leppäranta, Arkady Terzhevik, Nikolai Granin, Juliane Bernhardt, Christof Engelhardt, Tatyana Efremova et al. "Physics of seasonally ice-covered lakes: a review." Aquatic sciences 74, no. 4 (2012): 659-682.

Specifically, they introduce idea of Winter I and winter II as periods where heating is dominated by benthic heating (early winter) or solar radiation (late winter). I would say your lake is completely consistent with a long winter II dynamic. Another paper to better review is the GRL paper by Yang et al (2021), who introduce idea of cryomictic and cyrostratified lakes. Based on Figure 4 the lake on TP is windier than lake on Nordic tundra. there is no information on size of Kilpisjärvi Lake, but I assume that is much smaller than 610 km^2 Ngoring Lake (which is almost same size as 720 km^2 Lake Simcoe). Based on Yang et al (2021) you'd expect Ngoring Lake to be cryomictic and start winter near 0 ℃ before it warms up, whereas the smaller less windy Kilpisjärvi Lake to start winter nearer 4 ℃ as a cryostratified lake. I think the novelty of paper needs to be discussed in context of these two papers — This would change statement in abstract about warming dynamics that "The lake water temperature was observed to be generally rising during the ice-covered period from November 2015 to April 2016. This phenomenon appeared in the whole water column, with slowing in deep water and accelerating in shallow water before ice melting. The process is different from low-altitude boreal lakes. There are few studies on its mechanism and effects on lake-atmosphere interaction."

Reply: Thanks for your detailed consideration and constructive comments. Your advice improved the total quality of the manuscript. I have read the two articles carefully. We took your comments in deep consideration and revised the manuscript which we hope meet with approval. The **novelty** of this article is mainly reflected in the following three aspects:

1) In this paper, not only the influence of solar radiation on the warming up of under-ice water temperature was analyzed, but also the influence of other factors

(meteorological conditions and main physical parameters) was first quantitatively for the warming phenomenon.

2) Lakes with large surface area in mid-latitudes, especially those in dry continental climate zones, are snowless in winter. Winter II dominates the entire ice-covered period. During which convection mixing by radiative heating of upper water is dominant (Kirillin et al., 2012).

According to the maximum depth, surface area and wind speed, the lake can be divided into two types which are cryostratific and cryomictic lakes. The premise of two types is that the lake temperature does not exceed 4 °C (Yang et al., 2021).

Consistent with lakes of Winter II, solar radiation continued to heat up water during ice-covered period in Ngoring Lake. However, the upper water temperature in lakes of Winer II is less than 4 °C due to the heating is not intense enough, which in Ngoring Lake is more than 4 °C because of strong solar radiation.

Ngoring Lake mixed evenly when ice formed, that is consistent with cryomictic lakes. However, cryomictic lakes was mixed evenly until melting and the water temperature was less than 4 °C. While Ngoring Lake was mixed evenly in the early ice-covered stage and over 4 °C in the late stage, lake stratified after that.

3) The common lake model CLM-Lake and Flake applied into the Tibetan Plateau could not simulate this phenomenon, so the LAKE model that could do this was introduced into the study. If there was no the suitable lake model for the process simulation, it will hinder the study of the effect of plateau lakes on the atmosphere.

The information about Kilpisjärvi Lake is shown below:

Kilpisjärvi Lake (69.05º N, 20.83º E, 473 m a.s.l.) is an Arctic tundra lake with average depth of 19.5 m and maximum depth of 57 m. The lake has a surface area of 37 km^2. It is a cryostratified lake.

The statement in abstract about warming dynamics is unchanged, but the uniqueness is presented. The abstract not repeated here has been revised as the general response.

Specific comments

- The section from lines 79 to 104 needs to be completely rewritten. There is no need to discuss Lake Kivu which is a tropical merimoctic lake. If you want to talk about lake catergorisations, I recommend starting with

Lewis Jr, W. M. (1983). A revised classification of lakes based on mixing. Canadian Journal of Fisheries and Aquatic Sciences, 40(10), 1779-1787.

Then discuss 2012 of Kirillin and 2021 GRL paper by Wang et al. The other papers on winter dynamics of TP need to be better reviewed including

Wang, J., Huang, L., Ju, J., Daut, G., Ma, Q., Zhu, L., Haberzettl, T., Baade, J., Mäusbacher, R., Hamilton, A. and Graves, K., 2020. Seasonal stratification of a deep, high-altitude, dimictic lake: Nam Co, Tibetan Plateau. Journal of Hydrology, 584, p.124668.

Reply: Thank you and follow your recommendation. I have deleted the discussion about Kivu Lake and talked about lake categorizations starting with Lewis. Then focused on description of typical processes of under-ice stratification, the differences in lakes on the Qinghai-Tibet Plateau, and application of existing lake models in under-ice water.

The introduction has changed to the following:

"Seasonal lake ice is a part of the cryosphere, gaining recent attention from researchers due to its sensitivity to climate change (Kirillin et al., 2012; Sharma et al., 2020). The duration of ice cover affects the stability and vertical mixing of lakes, as well as the lake-atmosphere matter and energy exchange (Rösner et al., 2012; Efremova et al., 2013; Ramp et al., 2015). Ice cover regulates lake biochemical indicators, such as the concentration of dissolved oxygen, nitrogen, and phosphorus, changing the biochemical reaction rate and affecting the water quality and distribution of aquatic organisms (Weitere et al., 2010; Dokulil, 2013; Li et al., 2015a; Hardenbicker et al., 2016). Shortening of the ice season has been observed worldwide (Sharma et al., 2019; Dauginis and Brown 2021) and attributed to anthropogenic warming (Grant et al., 2021). Future climate predictions indicated the accelerated reduction of seasonal lake ice, especially pronounced in the lake-rich Arctic regions (Brown and Duguay 2011). Global assessment of seasonal lake ice changes requires quantification of the major heat sources and sinks on seasonal to climatic time scales. While the major prerequisite for the ice cover development is sufficient long season with air temperature below the freezing point of water, the heat budget of ice-covered lakes varies with latitude and altitude, depending strongly on the available solar radiation, the latter being the major source of heat for under-ice lake water (Kirillin et al., 2012). During the polar night in the Arctic and temperate lakes covered by snow, the solar heating is minor and the bottom sediment is the main heat source (Winter I according to Kirillin et al., 2012); at later stages of the ice season (Winter II), as the snow melts, solar radiation becomes to the main heat source governing thermal stratification and mixing under ice and the melting process at the ice base (Kirillin et al., 2018, 2020). Further, lakes with seasonal ice cover can be divided into cryomictic and cryostratified according to their maximum depth, surface area, and wind speed (Yang et al., 2021). In dry and cold areas with little snow, winter II can occupy the entire ice-covered period (Kirillin et al., 2012), making solar radiation to be the major factor affecting the lake ice regime. The situation is relevant to the alpine lakes.

In particular, the largest alpine lake system of the Qinghai-Tibet Plateau (TP), the highest plateau on Earth with an average altitude of 4000-5000 m ensures a high amount of solar radiation and low winter precipitation. The TP is covered by more than 1400 lakes with an area larger than 1 km^2, and the total lake area is more than 5×10^4 km^2, accounting for 57.2 % of that in China (Wan et al., 2016; Zhang et al., 2019). Recent studies reported the first observations from ice-covered Tibetan lakes, indicating the major role of solar radiation in their thermal regime (Wang et al., 2021). Water temperatures in Lakes Bangong Co and Nam Co constantly increased during the ice-covered period, with a stronger increase in shallower Bangong Co (Lazhu et al., 2021). Observations in meromictic Dagze Co Lake demonstrated stable temperatures in the early ice-covered period start warming only in the late ice-covered period, conditioned by the high water salinity (Wang et al., 2014; Lazhu et al., 2021). Salinity has a strong influence on the temperature and mixing regime of all three abovementioned lakes, by altering their density stratification and vertical heat transport. Among freshwater lakes in the TP, Ngoring Lake is the largest one (Kirillin et al. 2017, Wen et al. 2022). Kirillin et al. (2021) found strong solar radiation under ice cover heating the entire lake water column to the maximum freshwater density temperature (~3.98 °C, T_{md}) more than a month before the ice breakup—the situation never found in lowland freshwater lakes. As a result, strong heat release from water to the ice base turned into the major factor governing the ice melt, with the water temperature under ice achieving 6 °C. This radiation-dominated regime, differing dramatically from the typical heat budget known from earlier studies on ice-covered lakes, does not fall under the framework of the Winter I/Winter II classification, nor can be characterized in terms of cryomictic/cryostratified conditions. Quantification of the resulting heat balance and thermal stratification characteristic of alpine conditions is the subject of the present study.

Due to the harsh environment of the TP and difficulties in collecting field observations, numerical models are often used to investigate phenomena and mechanisms of TP lakes. At present, the widely used lake models are the FLake model and the lake scheme coupled in the CLM (Community Land Model), CoLM (Common Land Model), and WRF (Weather Research and Forecasting Model) (Lazhu et al., 2016; Wen et al., 2016; Fang et al., 2017; Dai et al., 2018; Huang et al., 2019; Song et al., 2020; Wu et al., 2021). However, for computational efficiency, winter dynamics in these highly-parameterized lake models are represented in a rather simplified way, lacking the detailed mechanisms of heating by radiation and resulting vertical heat transports across the water column (Lazhu et al., 2016; Wen et al., 2016; Huang et al., 2019). As an alternative, we adopt for this study a "classical" two-equation turbulence modeling approach proving its reliability in decades of studies on the environmental turbulent fluid dynamics. The one-dimensional model LAKE implements the approach in application to lake dynamics and was applied previously to different lakes (Stepanenko et al., 2011, 2016; Guseva et al., 2016). We combine modeling with in situ observations from Ngoring Lake, data on weather forcing and remote sensing to: (i) test the ability of a one-dimensional lake model LAKE to simulate temperature and stratification driven by intense solar heating in ice-covered Lake Ngoring; (ii) conduct series of sensitivity experiments aimed at revealing the role of meteorological forcing and ice optical properties in lake temperature and mixing regime; and (iii) reveal the effects of temperature distribution before ice breakup on lake heat storage and lake- atmosphere heat transfer."

- line 144 - is this lake salty like other TP lakes? this become important later when under ice temps go above 4 °C.

Reply: Thanks for your question. Ngoring Lake is a freshwater lake (0.27 g kg^{-1}, Shen et al., 2012), which is different from other lakes such as Qinghai Lake (12.3 g kg^{-1}), Selin Co Lake (18.7 g kg^{-1}), Nam Co Lake (1.7 g kg^{-1}) (Wu et al., 2021) and Zhari Namco Lake (14.8 g kg^{-1}), Dagze Co Lake (18 g kg^{-1}) (Lazhu et al., 2021). According to the simulation, lake temperature can exceed 4 °C without salinity, so salinity does not play an important role.

- Figure 1. Where is Nordic lake?

Reply: Thanks for your question. The Nordic lake in the original text refers to Kilpisjärvi Lake (69.05° N, 20.83° E, 473 m a.s.l.), which is located in northern Finland (Lei et al., 2012). The main research area of this paper is Ngoring Lake. Kilpisjärvi Lake provides its driving data as an auxiliary lake different from Ngoring Lake.

- What is bathymetry of lake - we more interested in that than topography. Where is water temperature sampled?

Reply: Thanks for your question. Ngoring Lake has a maximum depth of 32 m and an average depth of 17 m. Water temperature is measured at the WS point (35.03° N, 97.70° E, Figure 1). The bathymetry of Ngoring Lake and WS has been added in Figure 1.

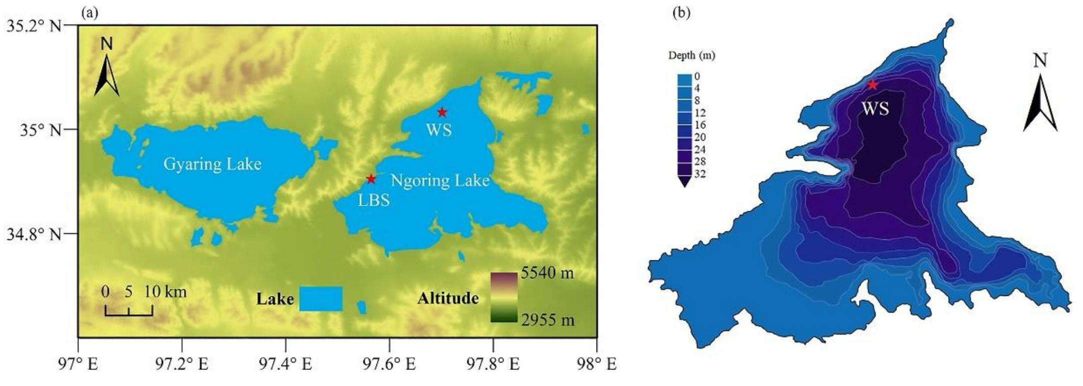

Figure 1. (a) Location of Ngoring Lake, the pentagram denotes the lake border station (LBS) and water temperature measurement point (WS). (b) The bathymetry of Ngoring Lake. (b) adapted from (Kirillin et al., 2021).

- line 168 - need to say specifically where profile was taken and add to figure 1.

Reply: Thanks for your advice. The water temperature measurement site (WS, 35.03° N, 97.70° E) has been added in Figure 1.

- Fgure 2 --Use a continuous shading, not something with 1 °C steps, when whole range of interest is really 0 - 4 °C

Reply: Thanks for your suggestion. Figure 2 has been revised with a continuous shading and 0.1 °C interval.

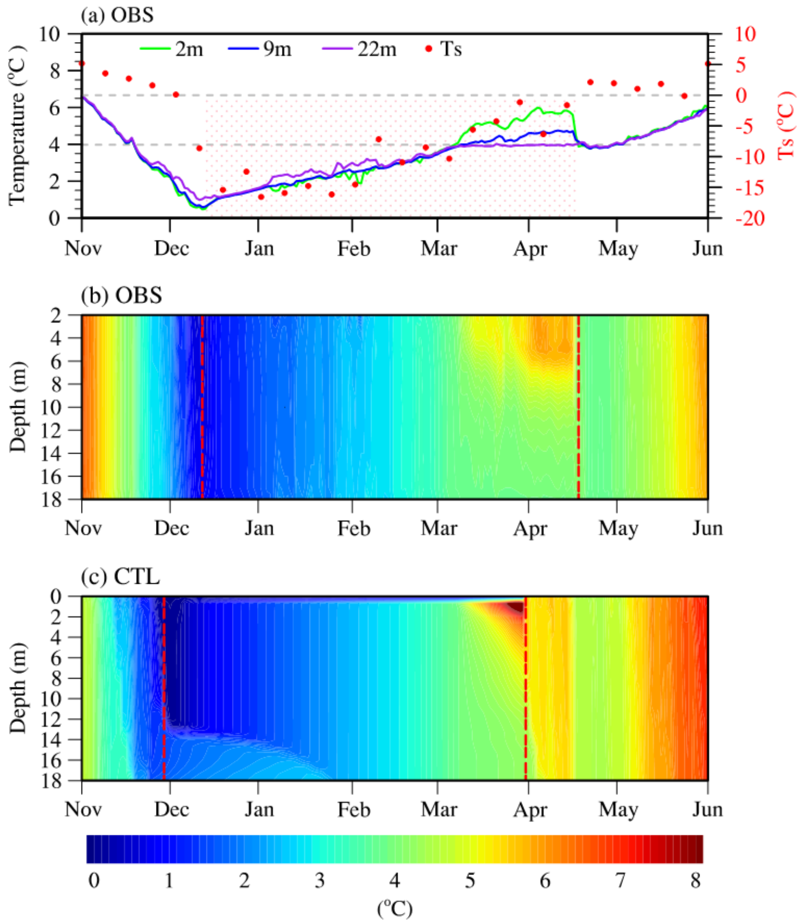

Figure 2. (a) The daily average water temperature observations of Ngoring Lake at the surface (Ts), 2 m, 9 m, and 22 m from November 1, 2015 to June 1, 2016. Ts is MODIS lake surface temperature. The gray reference lines denote 3.98 °C and 0 °C, respectively. The pink shaded area denotes ice-covered period. The water temperature profile (b) observed and (c) simulated in CTL. The ice-covered period is represented between the two red dashed lines.

- Line 308 - " Thereafter, the lake was mixed,.." You need a discussion in intro about Winter II and solar driven convection for this statement to make sense.

Reply: Thank you and follow your suggestion. I discussed the convection caused by solar radiation heating shallow water during ice-covered period. The following sentence has been added in Section 4.1.1:

"Ngoring Lake is mostly covered only by bare ice in winter due to drought, less precipitation and snow. In the early ice-covered phase (from December 12 to March 7), the whole lake mixed completely because solar radiation penetrated ice and heated the upper water, which was warm (< T_{md}), heavy and sinking (Fig. 2b) (Kirillin et al., 2012). In parallel, water temperature continued to warm until reached T_{md} on March 7 (Fig. 2a)."

- Line 329 - Don't abbreviate Kilpisjärvi Lake as K lake. It might be better to refer to it as lake Kilpisjärvi, as jarvi just means lake in Finnish. There are also no details on this lake - how deep how wide? Other publications on this data.

Reply: Thanks for your suggestion and the explanation about järvi. All abbreviations K Lake have been changed to Kilpisjärvi Lake in the revised manuscript and K changed to Kilpis in Figure 3. The details of Kilpisjärvi Lake (37 km^2, average depth 19.5 m, maximum depth 57 m) as described below have been added in Section 2.2.3:

"ERA5-Land data is applied for a comparative analysis of warming mechanisms and thermal conditions in Tibetan ice-covered lakes against those in the Arctic. The reanalysis forcing data for the geographical position 69.05° N, 20.83° E was adopted as "typical" arctic weather conditions. Northern Fennoscandia is covered by several lakes characterized by the longest ice-covered period in Western Europe. The largest of these lakes, Kilpisjärvi, has a similar morphometrical feature to Ngoring (average depth 19.5 m, maximum depth 57 m, surface area 37 km^2). The lake has been intensively studied in the last decades (Kirillin et al., 2015, 2018; Leppäranta et al., 2017, 2019). Its under-ice water temperature remained stable during winter from 1992 to 1993 (Tolonen, 1998). In the following, model experiments forced by the ERA5 weather data (1992-1993) for the Arctic refer to "Kilpisjärvi" runs."

- Figure 3 - use same x-axis formats for dates. Different data for temps is plotted so also hard to compare Y-axis of a and b.

Reply: Thanks for your suggestion. According to another reviewer's suggestion that deleting unimportant parts because the manuscript is too long, I have deleted the right panel of Figure 3 and merged the left panel with Figure 2.

- Figure 4 - comment on differences in wind speeds in driving one lake to be cyrostratified and the other cyromictic. The long polar night above artic circle drives Fig 4 b, so timing of magnitude of solar radiations drives most of differences in under ice convection.

Reply: Yes, I agree with you. Compared with Ngoring Lake, the wind speed of Kilpisjärvi Lake is relatively small, so Kilpisjärvi Lake is cryostratified lake which is deeper lakes or those with calmer winds, result in ice forming just above deeper waters of 3–4 °C (Tolonen et al., 1998). Due to the polar night phenomenon during Winter in Kilpisjärvi Lake, the variation range of lake temperature is small and remains stable for a long time.

- Line 370 - this question on under ice heating needs to better motivated by a revised introduction.

Reply: Thanks for your suggestion. The introduction has been revised.

References

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