Dear reviewer,

Thank you very much for your letter regarding our manuscript entitled “A field study on ice melting and breakup in a boreal lake, Pääjärvi, in Finland”. We are truly grateful to the comments and suggestions from you. The manuscript has been carefully revised, and the language has been checked. The point-by-point answers to the comments and suggestions were listed as below.

Response to Reviewer 2# Comments

The manuscript focused on the melting regime of lake ice, which has been seldomly investigated despite its crucial impacts on ice break-up, air-lake mass and heat exchange, and lake habitats and ecosystems. The manuscript, using varied technologies, investigated the melting rate, the evolutions of lake ice texture, pore, and crystalline structure, and the concurrent pH, EC, and Chl-a profiles with their relationships with the decaying ice. These observational results are quite important to understand the ice breakup regime and its effects on lake habitats and ecology.

However, the manuscript is too long and poorly-structured and is suffered to linguistic issues, so it is not easy to follow what the authors wanted to deliver to readers. E.g., there are a number of repetitions of sentences in the text, which can be removed or shortened. I am not sure of if the section 5.1 should be presented in Results or Discussion. I recommend that the manuscript should reorganized and carefully language checked when revising.

Intuitively, the manuscript is more like a report presenting the techniques and straight results than a scientific paper. It should be more focused and tightly compact on what you found and why. In short, the authors observed the melting rate, internal texture with estimated porosity, and basic ice+water geochemistry. It would better if the manuscript directly present the methods and results and discuss what controls the surface, bottom and interior melting, how these melting are related to the evolution of pH\EC\chl-a, and how it expands/deepens our knowledge on lake ice decay and accompanying changes in lake environment, so the interannual variations of ice breakup date and bearing capacity discussion seem redundant and not closely related to the topics.

Response: Thank you very much for your constructive comments and recommendation of the revision. We adjusted the structure of the manuscript to make it easier for readers to understand. We have adjusted our results, discussion and conclusions chapters. In chapter 3 (Results), we added sub-title for section 3.1 (Ice structure), and in section 3.3 (Ice geochemistry) we present the data of Table 5 in vertical plots which show clearly the vertical structures and temporal variations of EC, pH, and Chl *a*. We give a short and clear explanation in the text instead of repeating the numbers throughout long paragraphs. We transferred chapter 4 (Heat budget) to a new section 3.4. We removed all the results from chapter 4 (Discussion) to chapter 3 (Result) and give a revised discussion. Finally, we have rewritten the conclusions and give a clear summary about what we have done, the result and the meaning. We cut the repetitive descriptions in the manuscript and shortened the manuscript by 1/3. And we have checked the language. Please, see our responses to your comments as follows in more details.

L31: by/through altering the heat, mass…
Response: We have revised "Lake ice affects the local weather altering the heat, mass…" by "Lake ice affects the local weather by altering the heat, mass…".

L36: the under-ice living conditions or the living conditions under the ice
Response: We have revised "the living conditions under-ice" by "under-ice living conditions".

L43: please specify what the two major practical problems are.
Response: Thanks for your suggestion. In fact, we have given the two major practical problems in the manuscript, but we didn't make them clear. We revised this part as: "There are two major practical problems with melting lake ice due to the loss of strength caused by the ice deterioration (Ashton, 1985; Leppäranta, 2015; Masterson, 2009). First, ……. Second, ……". Then it is clear for readers.

Comment: L53-54: I guess "by about one week over 100 years" is actually true for e.g. boreal lakes? Should be specific here.
Response: Yes, you are right. Here we actually wanted to say in boreal lakes. We have revised "by about one week over 100 years" by "by about one week over 100 years in boreal lakes".

L67: the primary production
Response: We have revised "productive" by "production".

L69: limits the proper assessment of the impacts of…
Response: We have revised "properly" by "proper".

Comment: L71-90: I suggest this paragraph can be divided to several short paragraphs according to their key points. At its current status, it is not easy to clearly understand what the authors want to tell to the readers.
Response: Thanks for your advice. L71-90 was somehow confusing to read, we divided it into 2 paragraphs according to their key points. The first paragraph explained how the melting of ice occurs. The second paragraph showed how the internal melting and bottom melting occurs and the influence of internal melting and bottom melting. (Which can be seen in L70-87.)

Due to the difficult fieldwork conditions on deteriorating ice cover, there has not been much in situ research during the ice decay period. A snow cover delays the melting by its high albedo and low transmissivity of light (Ashton, 1986; Leppäranta, 2015; Warren, 1982). When the ice cover is snow-free, sunlight penetrates to the ice and through the ice. The ice warms up and melts inside, the under-ice water is heated, and the surface heat balance determines whether surface melting takes place (Kirillin et al., 2012). Ice impurities are released from melting ice into the water that changes the water environment. The under-ice light is also used for primary production, which normally peaks after ice breakup.

The present knowledge of the melting rate of ice is limited to a few studies, showing typical values of 1–3 cm d^{-1} in terms of equivalent ice thickness. Melting takes place at the top and bottom boundaries and in the interior depending on the weather conditions (Jakkila et al., 2009; Leppäranta et al., 2010, 2019; Wang et al., 2005). It has been found that the light transmittance changes with internal melting that has influence on further melting. Internal melting also opens channels for flushing the ice by surface meltwater and lake water. When the porosity of ice reaches the level of around 0.5, the ice cover collapses by its own weight and disappears rapidly (Leppäranta et al., 2010, 2019). Bottom melting is caused by the heat flux from water that can be large in spring due to the solar heating of the under-ice water (Jakkila et al., 2009; Shirasawa et al., 2006).

Comment: L91-98: I guess in this paragraph the authors should introduce briefly the scientific issues to be targeted, what work and analysis has been done, and what problems could be resolved. The snow and ice conditions may be better to be presented in the "2.1study site".

Response: Thanks for your suggestion. We have rewritten this paragraph as follows: We examine here the decay of ice in a boreal lake, Lake Pääjärvi, in southern Finland by field surveys in two years, 2018 and 2022. The objective was to analyse the ice melting process for the evolution of ice thickness and porosity as well as for the changes in ice and water geochemistry. The structure and properties of ice experienced remarkable changes during the decay process, and significant melting occurred in the surface and bottom and in the interior. Flushing of ice by meltwater and lake water caused changes to ice and water geochemistry. A deeper knowledge of the ice decay is needed for modelling the lake ice decay, particularly for ice engineering issues, and for understanding the physical and geochemical conditions for ecology of freezing lakes in spring. This paper gives the final results of the Lake Pääjärvi field program.

Comment: L125: delete "lateral"?

Response: Yes, we have delete "lateral".

Comment: L164: delete "Measurements of ice density can be found in several studies (Timco and Frederking, 1996)."

Response: We have delete "Measurements of ice density can be found in several studies (Timco and Frederking, 1996)."

Comment: L169-176: please add the measuring accuracy for each variable.

Response: Thanks for your advice. We have provided the accuracy values for pH (0.01) and EC (0.01 μS cm^{-1}).

Comment: Table 1: what did x and z denote?
Response: We have z no more and explain that "x stands for no data."

Comment: Figure 2: please add a scale to these maps.
Response: Thanks for your suggestion. We have added the spatial scales in Fig. 2. And we also added the color scale in Fig. 2.

Comment: L221: due to
Response: We have revised "due" by "due to".

Comment: (1): there must be mistakes in this equation since it was not consistent with the description bellow it and I cannot see L_f and Δt in the formula.

Response: Yes, we have revised the formula (1) in to " $Q = \frac{\rho_i L_f \Delta h}{\Delta t} = 13$ W m^{-2}".

Comment: L295-296: delete "In practice it is difficult to determine the freeboard/draft ratio as it requires an order of one-millimetre accuracy for the freeboard."
Response: We have deleted "In practice it is difficult to determine the freeboard/draft ratio as it requires an order of one-millimetre accuracy for the freeboard."

Comment: Table 5: It would be better if these data can be presented in a plot/plots (i.e., vertical profiles), which can show clearly the vertical structures and temporal variations of EC,pH, and Chl-a.
Response: Thanks for your suggestion. We presented the data in Table 5 in vertical plots which show clearly the vertical structures and temporal variations of EC, pH, and Chl *a*. Also, we made a short and clear explanation in the text for Fig.6 as follows: The vertical profiles of EC, pH and Chl *a* show that EC was larger near the snow-ice surface than in congelation ice in the early melting stage, but the difference was no more obvious after April 14. pH was always smaller in snow-ice than in congelation ice. Chl *a* content was less than 0.6 μg L^{-1} with the maximum at the snow-ice–congelation ice interface.

Comment: L322: how did the data of EC on April 14 confirm the deposition of acidic substances from the atmosphere? And why did EC of ice increase after a snowfall?
Response: Thank you very much, there was a mistake. We meant pH for the acidic deposit and even that was not a proof. Therefore, we wrote "Atmospheric deposition of acidic substances was judged as the background for the low pH of snow-ice." There was a little increase of EC of congelation because of the melting of the snow-ice and the meltwater drainage down. We have rewritten section 3.3 (3.3 Ice geochemistry) in the manuscript and given a clear explanation.

Comment: L333-334: "Algae can grow in a slush layer within snow-ice, but not in consolidated ice because of lack of liquid water for living organisms." However, Fig.

5b shows clearly the Chl-a content in congelation ice increases gradually as melting proceeds. The increase in Chl-a content within the ice is likely to result from the increasing solar radiation and/or the decreasing surface albedo rather than the thinning ice cover.

Response: Yes, you are right, the increase in Chl *a* content within the ice resulted from the increasing solar radiation and the formation of pores with liquid water in the congelation ice layer. This part in the manuscript was somewhat confusing and unclear. We revised the sentence by "Algae can grow under ice and in slush layers in ice all winter at sufficient photon flux conditions. In springtime algae growth occurs also in pores in ice containing liquid water. Chl *a* content was similar in under-ice water and in ice until April 26, but then it increased in water and became much higher than in ice at the time of ice breakup, but still well below the first summer peak."

Comment: (3): it would be better if you present briefly the physical meaning of each formula.

Response: Thanks for your suggestion. We have done what was requested. Considering also your following comments and the comments of Reviewer 1#, we have revised heat budget text. The daily meteorological data from FMI was used to analyze the ice melting in the heat budget. The albedo was parameterized as $\alpha = 0.7$ for snow, 0.5 for fry ice and 0.3 for wet ice. After the revised input data for the heat budget model, the results of model simulation are in good agreement with the observed results.

Comment: L359: 4 W m^{-2} cannot be a half of the incoming solar radiation in May.

Response: As said, $k_0(t)$ is not solar radiation but depends on the net radiation that includes both net solar and net longwave radiation. It is the part of the heat balance independent of the surface temperature, and the k_1 term then gives the correction due to the difference between air temperature and surface temperature (see the given reference). In Lake Pääjärvi site, $k_0 > 0$ in summer and $k_0 < 0$ in winter.

Comment: L363: does the bottom melting depend on the solar radiation?

Response: Yes it does, since sunlight heats under-ice water from where a part of the gained heat goes to ice melting. Indeed, Eq. (6) consists of the background heat flux from the deep water and a fraction c of the solar radiation penetrated to the water:

$$Q_w = Q_{w0} + c(1-\alpha)\gamma e^{-\lambda h} Q_{s0} \quad , \tag{6}$$

where α is albedo, γ represents the fraction of solar radiation that penetrates the surface, and λ is the light attenuation coefficient.

Comment: L367: what do you mean by "γ represents the fraction of light in solar radiation"? I guess it is the fraction that penetrates through the ice surface.

Response: Yes, you are right, we didn't make it clear for readers. We have revised "$\gamma \approx 0.5$ represents the fraction of light in solar radiation" by "γ represents the fraction of solar radiation that penetrates the surface (the light band)"

Comment: L368: by Qs0=150W m^{-2}, is it the daily-averaged value? It looks like a daytimeaveraged value in April. If this is true, Qs0≈75 W m^{-2}, the melt rate can be 0.16 cm d^{-1},close the observed rate of 0.18 cm d^{-1}.

Response: Yes, you are right, it's the averaged value in April. The FMI solar radiation data used now gives the average incident radiation in April as 184 W m^{-2}. E.g., take albedo as $\alpha = 0.5$, $\gamma = 0.5$ and $\lambda = 0.5\ m^{-1}$, and then the resulting absorption by ice is $Q_A = (1-\alpha)\gamma(1-e^{-\lambda h})Q_{s0} \approx 5-10\ W\ m^{-2}$ depending on the thickness h that corresponds to the observed melt rates.

Comment: (6): Could please give a brief physical background of this equation? What do the terms mean at the right-hand side?

Response: Yes. We have added a brief physical background of equation (6): "and the bottom melting in Eq. (6) consists of the background heat flux from the deep water (Q_{w0}) and a part of the under-ice solar radiation."

Comment: L389: the second "freezing" should be "melting"

Response: Here, the first "freezing" is "freezing days", the second "freezing" is "freezing dates", they are two different meanings. But in the revision of the manuscript, this sentence has been deleted.

Comment: L397: what do you mean by "the ice freezing days"? freezing duration, or ice-covered duration?

Response: Sorry we did not make it clear, it should be ice-covered duration. However, we have revised the structure of the manuscript, and this sentence has been deleted.

Comment: L433: after the net radiation becomes positive? The net radiation is always positive, I guess. And whether or not the surface, interior, and bottom melting take place depends on different conditions of heat balance.

Response: Thanks for your suggestion. Net radiation (solar + longwave) can be positive or negative. Anyway, we have revised this sentence as: Melting of ice begins after the heat balance becomes positive and takes place at the surface, interior and bottom depending on depending on the ice structure and fluxes.

Comment: L467: "Yang et al. (2012) modelled…too late", what do you mean?

Response: Sorry, it's language issues. It should be "The ice breakup date modelled by Yang et al. (2012) turned out to be 12 d late." However, we have revised the structure of the manuscript, and this sentence has been deleted.

Comment: L482: "Therefore, … on the structures.", what do you mean?

Response: Sorry, it's language issues. We did not make it clear. We have revised the paragraph as: The quality of ice decay is important to ice mechanics due to the loss of ice strength (Ashton, 1986; Leppäranta, 2015). There are two important consequences. First, the bearing capacity of ice (P) decreases. This quantity scales as $M \propto \sigma_f h^2$, where σ_f is the flexural strength, and during the melting period ice thickness and strength both decrease, thickness due to melting at the boundaries and strength due to internal melting. The positive albedo feedback in the melting process produces a patchy ice cover, and together with the unpredictable bearing capacity the ice cover becomes a severe safety issue. Secondly, the two-dimensional yield strength of a lake ice cover scales as $P \propto \sigma_c h/L$, where σ_c is the compressive strength of ice and L is the lake size length scale. With decreased thickness and strength, wind stress may lead to ice breakage and ice movement on shores, where damage can be caused to man-made structures since the ice strength is still finite.

Comment: L527: a surge of phytoplankton under ice may indicate a positive net production, which uses CO2 to produce oxygen and biomass, so why it results in an increase of CO2?

Response: Sorry, we did not give a clear explanation in the manuscript. The reason why CO_2 increased is that after the enhancement of biological activity, the total respiration in water is greater than photosynthesis, which leads to the increase of carbon dioxide content (Li, 2016). After we have revised the structure of the manuscript, and these sentences have been deleted.

Li, R. L.: Variations of Sea Ice and Sea Water Characteristics and Their Effects on Immune Enzyme Activity of Shellfish in Liaodong Bay, Ph.D. thesis, Dalian university of Technology, China, 130 pp., 2016.

Finally, according to the adjustment of the structure and content of this manuscript, the references of this manuscript are also adjusted accordingly.