Response to Reviewer #2.

We thank the reviewer for setting aside time to read and comment on our manuscript. The general impression of the manuscript being verbose was shared by other reviewers and we will do our best to improve language and structure. There were some questions and suggestions regarding other types of analyses. Some questions are answered in the paper, and some of the analyses are those that we would like to do, but cannot due to the lack of data. We will add a precipitation analysis, but there are other smaller analyses (such as snow depth) that we cannot perform. That said, we would also like to remind the reviewer that we are analyzing long-term historical changes in the breakup and not what drives the change the last 50 years. We have answered each question in more detail below.

RC2

Overall this paper presents a new long-term river ice record and examines changes in the breakup timing between three northern rivers. It first places the records in historical context and then compares them to temperature changes, and examines temporal changes including extreme timing of ice off events. Overall, while interesting, the manuscript reads as a bit verbose, and qualitative in places where perhaps some quantitative analysis could be used. There is some interesting information presented, and the long-term datasets analyzed together are a new contribution to the literature, but I think some of the qualitative description could be reduced to shorten the read.

We rewrote, rephrased, and deleted to improve clarity while also trying to make it less verbose. We can include another analysis (see more below) and we will add some more information about the sites.

The main thing I found to be lacking is the treatment of precipitation. The authors indicate quite correctly snow is important for breakup timing, not just with respect to delaying melt through high albedo as mentioned but also for the effect on the ice thickness. Also, when discussing ice break up – do the extreme events link to precipitation (rain or snow?) as well as temperature? Only temperature is compared. Can you include snow changes as well? derive a simple metric, perhaps total winter snowfall from typical freeze-up to break-up months? Or total winter/spring precipitation to include spring rainfall? I imagine the records may not go back as far as the entire river ice record, perhaps that is why they are not included. But some inclusion of precipitation in the analysis is important and I feel that is should be addressed with more detail when revised.

The reviewer is correct that there is no other data going as far back as the breakup series. This is one reason for compiling the breakup series and analyzing them together. In this article we aim to provide a new historical perspective of climate change/variability and not only focus on the events the last 50 years. Thus, there are analyses we would like to do, but there is no readily available data. There are some extra measurements from Torne River, however, there is no systematically collected data from the other sites. We will include some of these in section 2.4 where we will give a rough description of the conditions.

We will include a precipitation analysis. Concerning precipitation and extreme events. This is a good question that we would like to answer. Late extreme events do not relate to precipitation prior to the breakup, rather the lack of it. In the south, early extremes probably

relate to winter precipitation (wetter winters) or this is what on site observations seem to indicate (corresponding author lives in Turku). However, the lack of data means that we cannot address the question in detail.

The authors should add a map to show where the rivers are to provide spatial context.
We will add a map as this was also requested by other reviewers.

Some details are missing from the methods that I think will add more clarity.

Adjusting the dates to the vernal equinox is interesting and could use a bit more explanation of how that is done. When looking at the tables, its clearer that is the difference between identified date and the equinox is used, but 3.2 as written is not very clear. How was the actual equinox determined? Is this a dataset available somewhere with the timing listed for the relevant years before the calendar change? As someone who has never worked with datasets going back that far historically, I found this very interesting.

Thank you and yes, this is all very interesting. Especially reading descriptions from the 1700 and 1800s and seeing how they change when we go into the 1900s. Ice breakups were really entertainment on the highest level. The equinox dates are available from NASA. The given dates have been adjusted according to location (+2hrs). The methodology is explained more in-depth in our references. But we will try to clarify a bit more.

The temporally extreme events – I found this section confusing and after several reads still do not understand why 2 of the list of years were used. Can this be re-written more clearly? or explained why only 2 were used?

We will try to make it clearer. We are trying to explain how we proceeded when creating the tables when there were multiple years when the breakup occurred on the same date. We had to exclude some events and we are trying to explain that there is a method behind how we made the tables (which breakup years we included and why the others were excluded).

"In this analysis, we used the calendric dates to rank the breakups". – does that not skew some of the early records?

No, all the breakup dates in Torne and Aura rivers are already adjusted to the Gregorian calendar.

Section 3.5 – what is the model used for 1960-2020? More information is needed here to describe the data fully.

The method is fully described in two articles by Aalto et al. (2013, 2016) which are cited in the text. Moreover, we now also state in the manuscript as follows: "For the shorter 1960–2020 period, we used data based on a spatial model collected by the Finnish Meteorological Institute (FMI). Beginning in 1961, the model is based on temperature and precipitation data from Finland, and it is supplemented with data from neighboring countries. The model uses the kriging interpolation to account for the influence of topography and nearby water bodies (Aalto et al. 2013, 2016). The spatial variability in temperature and precipitation was explained using auxiliary information including mean elevation, sea percentage, and lake percentage for building a spatially and temporally continuous gridded dataset, with grid size of 1 km over the area of the country. Kriging with external drift was chosen by Aalto et al.

(2013) as the primary method due to its robustness and accuracy for this estimation, referring to an approach using external predictors (e.g. elevation) as covariates in the model."

RC2: Specific comments:

78-80: Are the other two study rivers regulated? I think not based on the sentence about the power plant boom but confirming would be good in the text. Comments later on about how the power plant may have changed the timing of break up but they focus on the thermal effects – did regulation have any effect with respect to water level?

Torne and Aura River are not regulated, this was noted in section 2.1. and 2.2. We focused on thermal breakups because these have made it more difficult to determine the breakup date. This is an important methodological aspect for the future any cryophenological series. If the breakup date cannot be established with certainty because the breakup process has changed (which is highly interesting), then it affects the validity of the series. This section was a bit unclear, so we improve it by giving a practical example as noted by the observers in section 2.4.

Regarding water levels as caused by the power plant, we have no data on the subject. But it is would be interesting to do a case-study with more local data (discharge in relation to the power plant, water level, precipitation and how it impacts power plant) if it is available.

112-113: "In Aura River, the records suggest that thermal breakups have delayed the ice-off date and this is because spring is the driest season in Finland (Irannezhad et al., 2014)." This could use a small clarifying sentence added that thermal break up would be later than mechanical break up since its thermodynamic rather than dynamic and the dry spring would reduce the runoff/melt. Its more or less stated in the sentences earlier, but an explicit sentence stating that would be useful. Also why more thermal now? is spring becoming drier?

In general, April is together with March two of the driest months in Turku and these are the months when most of the ice breakups/ice offs occur. Nonetheless, the sentence was poorly written and unclear (again) because it was a late editorial change that we were asked to do before submitting the paper. We will rewrite and move this to section 2.4 where we will also give a rough description of ice thickness and ice cover duration.

155-118: This whole bit is unclear to me. Lack of clear breakup dates because thermal melt made it challenging to determine the timing in Pori. Thermal break ups are delaying ice off because its dry. Then 'this' is because you are comparing ice off to ice breakup? I think you need to add some more info here on the timing difference between ice off and break up – you are comparing 2 different things. how much time generally passes between the two events on the Aura river? Is it consistent? (see comment later on this as well).

This was again poorly written and very confusing because it was a late editorial change that we were asked to do before submitting the paper. We will rewrite and move this to section 2.4. We will give an example from Pori. We should probably not mix in changes in the breakup process more than necessary. Please note that we are not comparing ice off events to ice breakup events, we are comparing the recorded dates of each event.

Regarding the process in Aura River see "Historical trends in spring ice breakup for the Aura River in Southwest Finland, AD 1749-2018" https://doi.org/10.1177/0959683619831429

255: How did you count thermal break ups and distinguish from dynamic? are they distinguished in the records?

We have not counted them for this article. The thermal breakups are often easily distinguishable from other types of breakups. In Turku, most citizens wanted an eventful breakup, so when a thermal breakup occurred, the observers clearly write their disappointment. For example, in the 1800s reporters describe the water level and how the ice melts in situ. Moreover, the Aura River meta-data also lets us distinguish the most dynamic breakups, i.e. the two extreme ends of the breakup process easily identified the last 180 years. Hence, there is much information that has not yet been analyzed, but these are all separate articles. We added some examples on thermal breakups from Pori, because it is important for the validity of the series.

316: April 16 and 15 respectively? Yes, changed.

343-346: Can you really compare the moving stake to breakup? is there a consistent offset? There is probably not a consistent offset. This is a bit of a conundrum.

402-404, 433: How do you define strong? Common pattern of variability, can you analyze statistically to quantify this? 'Strong' was a poor choice of words. Deleted.

449-450 and onwards: why is the change in the Kokemaki River actually an overestimation of climate change? Explain? The change in Kokemäki River, when compared to the change in Aura and Torne rivers, seems too great to be explained by climate warming. It is not impossible, but it seems unlikely that the change would be greater in Kokemäki River than in Aura River which is further south. Rewrote sentence to improve clarity.

476-479: Talking about projected temperatures. How about projected precipitation and possible effects on breakup? We will add a correlation analysis on precipitation so we will add precipitation to the discussion.

516: "Arguably, the warmer climate that is dominating in the south is changing more rapidly, and with less predictability, than the colder climate dominating in the north. A similar latitudinal shift has been noticed in Swedish lakes (HallerbaÌˆ ck et al., 2021; Weyhenmeyer et al., 2005). " Is this not because the temperature is closer to 0 in the lower latitude river reaches so a small temperature shift will have a more pronounced effect on the ice? This is seen in lake ice in near-zero regions compared to northern regions. This is highly likely. The metadata gives the impression that the conditions has already changed so much so that Turku has reached a threshold level were even a small temperature shift has significant impact on the ice conditions. The added section 2.4. that describes ice cover dates before the 1900 shows (to some extent) the magnitude of change when compared to the 2000s.

Table 2 has lines every 10 records but table 2 does not, I would suggest removing them from Table 1. Removed the lines from Table 1.