

Clim. Past Discuss., author comment AC2
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Reply on RC2

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Author comment on "Arctic glaciers and ice caps through the Holocene: a circumpolar synthesis of lake-based reconstructions" by Laura J. Larocca and Yarrow Axford, Clim. Past Discuss., <https://doi.org/10.5194/cp-2021-95-AC2>, 2021

We thank the two reviewers for detailed and constructive reviews that improved our manuscript. Our revisions are described point-by-point below.

Reviewer #2

The manuscript presents a compilation of all lake-based reconstructions of local glaciers and ice caps from the circum-Arctic. It describes each of the 65 lake records and synthesizes the data in summary figures from each of the seven regions. The data is very skewed towards Greenland and Scandinavia whereas there are less lake records from Russian Arctic and Arctic Canada. Overall, the data is well presented, and it provides an insightful discussion of the results in relation to other climate records. Accordingly, the paper thus falls within the scope of CP.

Thank you. We acknowledge this unevenness of the lake-based glacier records by adding the following sentence to Line 134: We note that roughly two-thirds of the available lake-based records are from Greenland and Scandinavia, while other regions (notably the Russian Arctic, Canadian Arctic, and Alaska) have less coverage.

I only have few suggestions that are meant to improve the manuscript.

Major comments

Figure 2 illustrates very well the type of threshold lakes that have been used in the compilation. I suggest that the authors also include a description of which proxies that are normally used in the studies i.e. XRF core scanning, LOI and magnetic susceptibility etc. It would also be relevant to mention the different types of dating methods and whether the reconstructions rely on macro or bulk ¹⁴C dating.

Thank you. We added the following sentence to describe proxies typically used to distinguish glacial and non-glacial sediments. Line 117: Typically, several geochemical and physical properties of sediment are measured (e.g., magnetic susceptibility, major element abundance, grain-size, color, organic matter content, and dry bulk density) and used to distinguish glacial and non-glacial sediments, and to infer glacier activity over time.

We highlight the dating method used in each study/reconstruction (specifically for the oldest Holocene age) by the colored bars in Figures 3-9, i.e., Line 243: Colored bars indicate the oldest reported Holocene age in each record (green= ^{14}C -dated plant or aquatic macrofossil, yellow=paleomagnetic secular variation (PSV), blue= ^{14}C dated marine macrofossil, pink=bulk sediment, purple=tephra, black=other).

The data is generally well presented in the summary figures. However, I have some issues with the way some of the lake records have been presented. For example, in figure 3 there are intervals in the lake records that are blank. What does that mean? Is it organic-rich sediments indicating smaller than present, or does it represent a hiatus? Another curious thing is that for many of the records a basal age is below the interpreted section. What is type of sediment is dated and how is it interpreted in relation to glacier history? Leaving intervals blank is not the best solution also because it is not mentioned in the text.

Thank you for requesting clarification. The black sections in figures 3-9 do not necessarily represent a hiatus, but more commonly a time period where the status of the glacier or ice cap is unknown or unclear. For instance, in records that are categorized as 'glacier-lake system 2', organic sediments may indicate a glacier or ice cap that is at present size, smaller, or absent. Thus, we cannot confidently define the glacier or ice cap status during those periods, and only include when the lake was glacially influenced in our core schematics. In other cases, blank sections indicate times when glacier or ice cap status was unclear or not defined in the original study. To clarify this for readers, we updated the glacier/ice cap status key in panel A for figures 3-9. We also added the following text in the figure 3 caption: Line 246: "... and blank sections denote times when glacier or ice cap status is unknown or unclear."

In cases where the oldest Holocene date is younger than the oldest interpreted sediments, the original study either (1) included a pre-Holocene date, or (2) extended their age model past the oldest date to the base of the core.

Another thing that would help the interpretation is if the individual records are arranged according to which type of threshold lake, they represent i.e. type 1-3.

Although we prefer to arrange the records by glacier/ice cap elevation, we agree with the suggestion to add the "type of threshold lake" and we have added a symbol to each record in Figures 3-9 (to the right of the site # in panel A) that corresponds to the glacier-lake systems (1-3) that we defined in Figure 2. We hope this will help with the reader's interpretation of the individual records.

Minor comments

I would use Early, Middle and Late Holocene as the subdivision of the Holocene has been formally defined by IGS.

We used subdivisions at 8.2 ka (to divide the early and middle Holocene) and 4.2 ka (to divide the middle and late Holocene) following Walker et al. (2018). We added the following sentence in section 2 Data and approach, to explicitly state this: We subdivide the Holocene with the early, middle, and late Holocene beginning at 11.7, 8.2, and 4.2 ka, respectively.

Line 72. Change homogenously to synchronously

We revised line 72: Likewise, the onset and rate of summer cooling in the Arctic

in the middle-to-late Holocene did not occur concomitantly.

Line 116. Maybe cite some of the pioneering threshold lake records i.e. Karlén 1981

We revised line 116: The records report local GIC fluctuations through the Holocene reconstructed via analysis of lacustrine sediments from downstream glacial lakes (e.g., Karlén, 1976, 1981; Leonard, 1985, 1986; Karlén and Matthews, 1992).

Line 128. I get the number of lakes to 65 not 66?

In the original paper submission, there are 66 lake-based records plus 1 non-lake-based record from the Russian Arctic. We include a supplementary table listing all the included records.

Line 284-285. Maybe explain why the records are excluded in some more detail.

We accept all published lake-based Holocene records of glacier fluctuations that clearly define mountain glacier or ice cap status (i.e., specifically if/when they were smaller than present or absent and/or when they regrew in lake catchments) and with sufficient age control to define their status in time. In general, we also make an effort to mention and briefly describe any lake-based Holocene glacier records that we do not include in their respective regional sections so that the additional and valuable information provided is not fully excluded.

We revised 131: We excluded ambiguous records (that do not clearly define when GICs were smaller than present or absent, or when they regrew) and records with poor age control and included one non-lake-based study from the Russian Arctic (due to the dearth of published glacial lake records there).

Line 304. I have found a couple of records that have not been included in the compilation.

Søndergaard et al 2019 concerning the local ice cap at Qaanaaq and a study concerning Gletscherlukket in SE Greenland by Larsen et al 2021.

Thank you for pointing these records out.

We did not include Søndergaard et al. (2019) in our compilation because the proglacial lake record (referred to as Lake Q3) is used to constrain an integrated signal of ice fluctuations of outlet glaciers of the Greenland Ice Sheet and the Qaanaaq Ice Cap through the Holocene. Since the lake record could not distinguish ice fluctuations of Qaanaaq Ice Cap alone and our study focuses on local glaciers and ice caps distinct from ice sheets (since ice sheets have much longer response times to climate perturbations), we omit this study. However, we have added the following sentences to acknowledge this work. Line 419: Just north of North Ice Cap, Søndergaard et al. (2019) infer the glacial history of outlet glaciers of the Greenland Ice Sheet and the local ice cap, Qaanaaq Ice Cap, via analysis of lake cores from proglacial lake, Lake Q3, geomorphological mapping, ¹⁰Be exposure dating, and ¹⁴C dating of reworked marine mollusks and subfossil plants. The lake record suggests continued glacial meltwater input from its formation at ~7.2 ka until present (Søndergaard et al., 2019). However, since the record cannot distinguish if the sediment deposited in Lake Q3 originates from the Greenland Ice Sheet, the Qaanaaq Ice Cap, or both, and our study focuses only on glaciers and ice caps distinct from the ice sheets, we do not include this record in our compilation.

We did not include Larsen et al. (2021) in our compilation due to insufficient age control. Larsen et al. (2021) present sediment records from two threshold lakes, Lakes XC1423 and XC1424, in southeast Greenland. At present, the lakes do not receive meltwater from the local glacier, Apusiikajik Glacier, as the glacier retreated out of the catchment sometime prior to 1932. During the LIA, the lakes received meltwater when the glacier was at its maximum position. The lake records show that Apusiikajik Glacier receded out of the lake catchments by ~9.6 ka and remained smaller than its LIA extent until its Late Holocene readvance. However, the timing of the late Holocene readvance is not clear as ages below the silty-clay suggest glacial meltwater input from Apusiikajik Glacier at ~0.5 or 0.2 ka. We have added the following sentences to acknowledge this work. Line 359: Larsen et al. (2021b) present a Holocene record of Apusiikajik Glacier from two threshold lakes (Lakes XC1423 and XC1424) in southeast Greenland at roughly 63°N. The lakes do not receive glacial meltwater at present as the glacier retreated out of the catchment sometime prior to 1932 CE. The lake records show that Apusiikajik Glacier receded out of the lake catchments by ~9.6 ka and remained smaller than its LIA extent until a readvance in the late Holocene. However, the timing of the readvance is not well constrained, as ages below the silty-clay suggest glacial meltwater input from ~0.5 or 0.2 ka (Larsen et al., 2021b). Thus, we do not include this record in our compilation.

Line 372. I would leave-out the information from the subfossil plants – otherwise similar data from other sites should also be included.

We deleted this point, i.e., we deleted the following line: Radiocarbon dates from subfossil plants provide strong evidence that the ice cap was smaller than present from AD 200 to 1025.

Line 471-478. It is correct that many of the lakes presented in Schomacker et al 2016 are not threshold lakes that receive meltwater at present. However, it is not correct that it does not provide any constraint on the glacier history. One of the lake records receive meltwater from Drangajökull until c. 7.2 ka suggesting the ice cap was larger than present until the Middle Holocene. It would be relevant to add this information.

Thank you for pointing this out. We added the following: Line 503: The lake records also suggest that the northern part of the ice cap was at a similar size or smaller than today by ~10.2 ka whereas the southeast part of the ice cap was larger than today until ~7.8–7.2 ka (Schomacker et al., 2016).

Line 733-742. Why include this information in a compilation of lake records

We included the additional non-lake-based record from the Russian Arctic because of the unique dearth of lake-based information on Holocene glacier fluctuations there. Since Lubinsky et al. (1999) provide the most comprehensive overview of Holocene glacier fluctuations and report information from 16 glacier margins in Franz Josef Land, we decided to include a summary of that evidence in our compilation.

Line 794-796. I am slightly surprised that there are no differences between the lake-based reconstructions and the patterns of GIC fluctuations presented in Solomina et al 2015. It would also be relevant to describe where lake-based records have an advantage and disadvantage compared to other types of proxies used in Solomina et al 2015.

Our compilation shows that the majority of Arctic glaciers and ice caps were smaller than present or absent by ~10 ka, and that most were smaller than present or absent between 7.9-4.5 ka. This finding broadly agrees with Solomina

et al., 2015, in that their synthesis finds that in most regions of the mid to high latitudes of the Northern Hemisphere, glaciers were smaller than present or at least equal to their modern sizes between ~8-4 ka. However, the main advantage of our synthesis is that the lake-based records provide unique direct evidence for periods of smaller-than-present ice extent regionally and Arctic-wide.

We revised the final paragraph in section 3.8: Solomina et al. (2015) present the most recent global review of Holocene glacier fluctuations and find that Northern Hemisphere, mid-to-high latitude glaciers were smaller than present or at least equal to their present sizes ~8-4 ka (Solomina et al., 2015). Similarly, a recent study investigating Neoglacial cooling in the Arctic developed a simple index to summarize the relative extent of GICs in Arctic regions (the status of which were derived from the above global review) and reported that GICs were retreated throughout the Arctic ~8-6.5 ka (McKay et al., 2018). The study suggested that this period of uniform retreat, and by inference widespread warmth, can be attributed to high summer insolation combined with the absence of (or lessening influence of) the Laurentide Ice Sheet which lingered well after peak insolation, as late as ~7 ka (McKay et al., 2018). Although our Arctic dataset broadly agrees with other syntheses of Holocene glacier status, our focus on lacustrine archives provides unique direct evidence for periods of smaller-than-present ice extent, and Arctic-wide suggests that most GICs first became smaller than today in the early Holocene.

Line 830. Other forcings – which?

Kaufman et al., 2004 provides a nice review of these other forcings and feedback mechanisms. We revised line 830: This marked variability speaks to the complexity of the Arctic climate system's response to insolation, local modulating factors such as ice sheet and ocean influences, and feedback mechanisms (see Kaufman et al., 2004).

Line 955. Many shrank than today in the Early Holocene. I am not sure if that holds. Maybe change to some or even better write x out of y GICs shrank....

Out of the 54 records that provide information on glacier/ice cap status in the early Holocene, 46 (or roughly 85%) showed that the glacier/ice cap first became smaller than present or absent sometime in the early Holocene (i.e., prior to 8.2 ka). For clarity we have changed the text to read "a large majority" instead of "many."