Kas Glacier Paper; Second Review

Reviewer 1 comments;

General comments

This study provides a characterization of an understudied system, combining a variety of observational perspectives. In my estimation, some of the major concerns raised by the reviewers and editor have been addressed, while others still need some revision. I believe that the presented data are definitely worth publishing and provide valuable insight into the recent (last decade) development of KG and KGL.

Thank you for your kind and carefully considered review, which we feel has been a great help in further improving the manuscript.

However, the stated aim of the study stated in the research question (L53) and objective 4 (L64) does not quite match what the data and analysis accomplish. Lake warming – which is presented as a central point in the research question – is only inferred rather than directly or indirectly measured. There is however evidence for comparatively high lake temperatures, which in my opinion is justification enough to publish. Consequently, I believe the framing of the study needs to be slightly adjusted to fit the data at hand. In my view, the strong points of the study, supported by a lot of observations, are objectives 2 and 3, which should receive more emphasis.

We have changed 'warming' to 'temperatures' in line 53;

This study aims to investigate the relationship between glacial lake temperatures ~~warming~~ and glacier retreat, (on a decadal and seasonal timescale) at a previously unstudied Arctic glacier through remote sensing and in situ measurements.

We have refrained from re-numbering the objectives as they are numbered to reflect the current flow of the paper (rather than by importance) – as each subsection is currently ordered to follow the objective order. We could letter the objectives a,b,c,d if it removes the suggestion of ordering by importance that numbering gives?

Similarly, one might argue that a regressive lake bed topography (which is not well-constrained in the area of recent retreat) could lead to accelerated retreat rather than warming temperatures or a combination of both. Generally, the data on lake temperatures are quite limited – in particular spatially. It is my opinion that this data should not be overused to infer lake properties. Instead, it should be recognized as a limitation more explicitly.

Thank you for raising these important points. We have further temperature data showing very similar near surface temperatures (~3.5 to 4°C) from a series of boat surveys; which we are happy to make available on request (such as in a data repository or in the Supplementary). We feel that the thermistor data presented here is from important strategic positions; next to the ice front at 1m depth (note; North facing so remained in shadow), next to the ice front at ~20m depth (where cold dense meltwater may have been expected) and at the central point of the lake at 5m depth. We feel that these strategic sampling points provide a fairly sound representation of the lake characteristics during 2019; particularly as other locations in the lake were more prone to iceberg disruption (such as near the outlet as experienced in 2017).

We argue that there was little evidence of mechanical calving in the 2017 or 2019 field season, as crevassing was inconsistent with either extensional flow or buoyant forces. Given the thinning of the terminus (and likely cold based ice) it seems logical to argue that mechanically driven calving during earlier periods was less likely, so depth would likely have lesser importance on calving mechanisms. Although we can't conclusively eliminate the possibility of a shallower area in the bathymetry data gap, so we have made the following amendments;

Line 177

The bathymetry survey revealed that central parts of the terminus remained in relatively deep water during the survey period (2008 to 2019) but note the gap in sonar bathymetry data in this area (grey area; Fig.2).

Line 307

Unfortunately, a gap (~50 m across) in the sonar survey of KGL remains, but we suggest that the gap bathymetry is likely to be similar, as it is too small to have a substantial over-deepening and there is no obvious evidence for any substantial shallowing (such as a bedrock riegel or moraine) as large icebergs passed to the lake mid-point.

Line 426

Whilst variability in mechanical support due to lake depth cannot be conclusively eliminated (due to data gap in the bathymetry) we argue that mechanical calving processes are not the main driver of recession of KG terminus, due to the factors discussed above and factors further discussed in the next section.

Finally, in my experience reading the paper, it remains quite challenging to keep track of the different datasets collected at various points in time. Perhaps the publication would profit from a data collection overview in the form of a table and/or timeline.
Thanks for the excellent suggestion. We have added one at the start of the Methods (Table 1).

Specific comments
1. The bathymetric survey is also spatially limited and some subsequent characterizations of the lake bed (L175-177; L306-310) are likely a result of the interpolation using these sparse measurement points. It is unfortunate that the areas without (or with only very limited) bathymetric data are exactly where the terminus was more stable and then started retreating rapidly from. In my view, this should also be acknowledged more clearly as a point of uncertainty.
Thank you for the insightful review comments. We have revised the following sections accordingly;

Section 4.1

“whereas the eastern margin is likely to deepen (>5m) steeply within 10m of the shore (note sparser depth points on E margin; see Supplementary S1).”

Section 5.1

“Unfortunately, a gap (~50 m across) in the sonar survey of KGL remains, but we suggest that the gap bathymetry is likely to be similar, as it is too small to have a substantial over-deepening and there is no obvious evidence for any substantial shallowing (such as a bedrock riegel or moraine) as large icebergs passed to the lake mid-point.”

Section 5.4.2 2019 Field Season

Whilst variability in mechanical support due to lake depth cannot be conclusively eliminated (due to data gap in the bathymetry) we argue that mechanical calving processes are not the main driver of recession of KG terminus, due to the factors discussed above and factors further discussed in the next section.

Section 5.5 – Wider Implications

“Comprehensive sonar surveys of the ice proximal lake bed are essential to identify any possible shallower areas that may have provided sufficient support to maintain terminus position stability.”

2. The observations of the calving front are well-supported by data – though some interpretations seem to rely on time-lapse footage. Maybe these videos could be included as a supplement.

We have included the timelapse video in a Zenodo repository (included in Assets); https://zenodo.org/records/16631366?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6IjI0M2M2NDAzLTEzMWUtNDUxZS1hYWNlLTNjOTBlYjkwOTBmNSIsImRhdGEiOnt9LCJyYW5kb20iOiIwM2VhYTkxMTQyZTZlYWI0NTk5N2Q5MTBlNzZmNjhkNiJ9.KsC_4akPRzK_sykp4_mgkJqGVQxWTG5o7TYJIqKKXeSp0SqUTBfo7S46Ki7ojVniNaHqMjNM4Yp8AAZziNLvew

https://doi.org/10.5281/zenodo.16631365

3. Debris-covered areas of the glaciers appear at some point in the discussion, they could quickly be mentioned in the study area description.

Thanks for the suggestion, we have added the following (in blue) to the Study Area section;

Kaskasapakte Glacier (KG) is ~2 km long and flows northeast from two subsidiary corries (located below ~500 m headwalls, with peaks of ~2,000 m asl to the east, south and west) into the main trunk; currently terminating in a calving front in an unnamed proglacial lake (now referred to as KGL) with some latitudinal supraglacial debris bands near the terminus (Fig. 1 and see Supplementary for images).

4. I assume that light intensity (L267, Fig. 7) is used as an indication of whether the thermistor was moved from its intended position, maybe this could be shortly explained somewhere in the methods.

We have amended the following section;

3.4 Lake water and meteorological changes through the 2019 melt season

Summer 2019 lake water temperatures were measured at 1 m depth on a line suspended from the glacier terminus (67.95396 N 18.55955 E) using a HOBO UAA-002-08 pendant to measure hourly temperature (± 0.5 ºC) and light (so periods of solar warming from sensor disruption could be identified for quality control).

5. In section 5.2, the addition of ITS_LIVE velocities makes sense to get a rough estimate of ice dynamics. Still, I think the two concepts of (local) mass loss (which is well-constrained from your data) and mass balance (where the dynamics are an unconstrained component) need to be separated clearly. As it is worded now, "volume of ice lost" (L323) could refer to either of these quantities.

Thank you for raising this important point and apologies for the inconsistencies that were present. We have included a sentence at the start of section 3.3.1 to clarify and have made changes to consistently refer to 'static volume' change;

"We calculate 'static' glacier volume change for geometric differences between glacier surfaces in the lower part of KG, as insufficient velocity data prevented dynamic processes being incorporated."

Section 4.2

Ice surface velocities derived from NASA ITS_LIVE feature tracking were below ~ 40 m y^{-1} (see S6; Gardner et al., 2019) but high uncertainties prevented incorporation into geometric calculations; so presented volume changes are essentially 'static' as dynamics were not incorporated.

Section 5.2

There has also been substantial surface lowering of KG between 2015 and 2018, with changes of 7 to 8 m extending 200 m back up glacier across the front, with 774,374 m^3 reduction in glacier volume ~~ice lost~~ in the 2019 ~~ablation~~ terminus area between 2015 and 2019 (RMSE = 0.52 m; Fig. 4).

6. One of the processes only touched on briefly is water entering the lake from sub-/englacial meltwater channels. To me, what happens with incoming meltwater seems quite relevant to the thermal state of the lake. Was there any indication that a plume formed, bringing cold water to the surface? Or would you expect sediment-rich (at least temporarily denser) meltwater to remain at the bottom of the lake? Is this significant to the circulation in the lake?

Excellent points. I have added this to the start of section 4.4. Calving Mechanisms;

"Buoyant plumes were not observed at the ice front."

At the time of observations in 2019 the lake was relatively well mixed, with temperatures from thermistor 1, 2 (central) and 3 (terminus deep) all between 3.5 to 4°C. We also have near surface temperature readings from boat surveys between 3.5 to 4°C and would be happy to share this data. This was following a period of north easterly winds blowing down the lake, which likely mixed the lake given it's relatively shallow depth. We agree that lake thermal stratification can have a strong influence on the subaqueous glacier profile, as has been reported from Patagonia (Sugiyama et al., 2016). Given the relatively simple lake thermal stratification observed in 2019, we have refrained from discussing how Kas Glacier lake thermal stratification may vary over time in this paper, as we feel that would be best left for a more detailed process based paper. We have made an addition in section 5.5 Wider Implications to highlight this;

This study provides an observational overview of the system and future research should focus on the evolution of subaerial and subaqueous lacustrine glacier termini (in conjunction with lake thermal stratification), particularly given future predictions of air temperature increases and associated reduction of lake ice cover duration, which will expose lake water to greater warming influences (Huang et al., 2022).

7. L417/418: the longitudinal supraglacial debris ridges at the margins do not look like thrust debris (of subglacial origin) to me, which is the type of debris cover the sources you cite refer to. Rather I believe the debris to be of supraglacial origin – through rockfalls and avalanches – as it is common on debris-covered glaciers. You can even visually trace the debris transport up-glacier to individual rock walls. I would not use these features as clear evidence for cold ice at the margins.

Thank you for your excellent points regarding the supraglacial debris and we apologise that we had removed an image from the supplementary that showed latitudinal debris bands more clearly. I have included an image of the terminus from 1988, which has clearer debris bands extending laterally across the terminus. These are similar to those cited visually, but we are unable to confirm whether the debris is subglacial or supraglacial. Given the lack of radar data from this glacier we would like to include this evidence, whilst it is relatively weak we feel it helps to pose an important point as to whether cold based ice from the terminus has been removed by calving.

We have amended the second paragraph in section 5.4.3 Mechanical Calving to;

Unfortunately there is no existing radar survey to confirm the thermal structure of KG. However, we argue that the margins and terminus are likely to be frozen to the bed (as at neighbouring Storglaciaren) as water filled crevasses persisted through the melt season and the supraglacial debris bands seen near the terminus of KG (see Supplementary 6) are typically associated with the transition of temperate to cold based ice (Moore et al., 2011; Monz et al., 2022; Carrivick et al., 2023).

8. The legends, captions, and axis labels in the supplement could be improved:
- In S1, one part of the legend is in the figure and another part as text in the caption
Thanks for identifying this, we have now labelled the ground control points on the figure as we feel this is consistent with the other labelling.
- In Table 1, it is not clear which observations the data originate from (probably time-lapse?)
Ah. Apologies for the oversight. Now amended to include timelapse information. REPOSITORY?
- In S4, axis labels are missing altogether
Thanks. Amended.
- In S5, three of the five subfigures are labelled a-c, which is not reflected in the caption

Technical corrections
L159-162: Somehow two sources of precipitation data at the same location are mentioned here (SMHI and SITES).
Thanks for the observation – there was a change in operator of the AWS.
L173/174: this sentence does not quite add up to me.

Thanks. We have tried to clarify this sentence further by adding "only" and "; as they are";

Whilst these satellite images represent only a snapshot in time, we report them here as there is noticeable variation between 2008 and 2019 that should be considered in the context of lacustrine terminus geometry changes; as they are over time periods that are important to the typical progression of thermal undercutting by a proglacial lake.

L187: I think this heading is a bit misleading, as the data presented in this section only represent a single state of the terminus rather than change

Excellent point – 'change' deleted. Thanks.

Fig. 4: not sure if this is the best colour scale – to me the green areas intuitively represent mass gain.

We experimented with different colour schemes but felt this was the best available one in QGIS and feel the legend clarifies that there is no increase in volume.

L216: This sentence is still a bit confusing and should be formulated more clearly.

Ah sorry for that! Thanks. We have reworded it to;

"Removal of the 2015 glacier ice surface down to the 2019 lake level, varied between 0 to 23 m in height across the pink polygon area (Fig.4)."

L217: there is no Figure 4a, probably Fig. 4 is meant here.

Thanks. Amended to Fig.4

L221/222: are these 30.2% calculated based on the entire ablation area or just the black outline from Fig. 4?

Thanks for identifying this – we have deleted '~~ablation area~~' and now refer to 'terminus area (black and pink polygon)' instead.

Fig. 7: the colours in subfigure d) do not quite match the legend and c).

Apologies for this, it is due to the mismatch between the colour scheme from Python and from the graphics software. We feel that they are distinguishable still.

L320: unit consistency; use either m y-1, m yr-1, or m a-1 throughout the entire text.

We have now eliminated m a^{-1} and ensured m y^{-1} is used consistently.

L359/374: these headings could be more descriptive, they currently look more like placeholders.

We have changed these to;

5.4.1 2017 Field Season Changes in Glacier Front

5.4.2 2019 Field Season Changes in Glacier Front and Environmental Conditions

L452/453: this sentence does not quite add up to me.

Thanks. We've reworded it to;

This study provides the first (to our knowledge) direct field evidence of ~~an~~ Arctic glacier recession~~retreat~~ being enhanced by contact with warm (>4 ºC) proglacial lake temperatures, through rapid thermo-erosional undercutting and associated calving.

Reviewer 2 comments;

The authors have revised their manuscript in line with reviewer suggestions and I appreciate the authors detailed responses and explanations. I am satisfied my comments have been carefully considered and the authors responses are thoroughly justified. It is clear to the reader what the study aims to achieve and the methods and datasets are now more transparent. As such, I think the manuscript is much improved, making a significant contribution to glacier lake observations and providing important data with which to refine and validate glacier evolution models, for example. The minor comments below are just personal preferences but not at all detrimental to the paper if they are not acted upon.

Thank you for the carefully considered review.

Lines 68-70 – 'Two periods of fieldwork were conducted (between 23rd July-4th August 2017 and 29th July-10th August 2019) at an unnamed proglacial lake (now referred to as KGL) in the Kebnekaise massif (Arctic Sweden), into which Kaskasapakte Glacier (KG) terminates. Further sonar bathymetry surveys conducted in August 2022 are also included.' I think these sentences are better suited to the beginning of the Methods section and an alternative introduction to the Study area.

Thanks – I've moved these to the Methods section (which has improved the start of that section too).

L94 – insert 'Swedish' before Lantmateriet?

Done. Thanks.

L136 - Changes in surface elevation of KG between 2015-2019 'was calculated' by subtracting...?

Thanks. Added!

L155 – 'Arches are defined as features where depth is less than height of the overhang, whereas caves are where depth is more than the height of the overhang.' Sorry, I'm not sure I entirely understand this sentence, depth of what?

Apologies for the confusion here. I've hopefully clarified that sentence a bit further to;

"For classification of larger undercut features in the subaerial ice front (above the waterline notch); arches are defined as features where depth of the overhang was less than its height , whereas if the depth of the overhang was~~is~~ greater than its height it was defined as a cave."

L182 – is it a shallower 'bedrock' shelf (?)

It wasn't possible to identify whether this shallower shelf was predominantly composed of moraine or bedrock. I've just added '(bedrock/moraine composition unknown)'.

L264 – 'Water temperatures were monitored in the ice proximal area (at 1 m depth; Fig.7) from 29th July to 28th August 2019' – Would it be useful to report the average temperature in brackets?

Yes! Excellent suggestion. Added.

L284 – Fig 7 caption – ‘1 m depth next to the glacier terminus’ – it’s a little unclear if the thermistor string was parallel to the glacier terminus, or if it’s a single point?

Ah! Thanks for spotting this and sorry for the confusion – I’ve tried to iron out the inconsistencies and added the following sentence to section 3.4;

“Summer 2019 lake water temperatures were measured at 1 m depth on a line suspended from the glacier terminus… A thermistor was positioned lower down (at 2m depth) parallel to the ice front, but this was removed by a calving event.”

L450 – ‘observed in order to understand what changes in balances at the ice front that may trigger periods of frequent calving activity.’ – Suggest deleting ‘that’

Thanks. Done

It might be useful to add the temperature measurement locations as points on Fig 1 to provide some context.

Yes, I see what you mean. It wouldn’t work on Fig.1 as it’s from 2008. Unfortunately we couldn’t get hold of a high quality satellite image from 2019 to plot the thermistors at the relevant positions – it’s very shady!

I’ve added them to Figure 2 (and referred to it in the text) – I think that should work and it’s important to see the lake depth context for each thermistor I think.