

Atlantic water access and the break-up of the C.H. Ostenfeld Gletsjer ice tongue, Northwest Greenland

Corresponding Author: Professor Martin Jakobsson

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Professor Jakobsson,

Your manuscript titled "The Role of Atlantic Water in the Break-up of C.H. Ostenfeld Glacier's Ice Tongue, Northwest Greenland" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

In particular, please ensure that the revised manuscript meets the following editorial threshold:

*Ensure that all conclusions are fully supported. In particular, conclusions linking Atlantic Water warming in Fram Strait and CH Ostenfeld Glacier disintegration should be either compellingly supported by additional robust evidence or, if such support is lacking, softened in a re-focused revision.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:

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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Shin Sugiyama, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0001-5323-9558

Nicola Colombo, PhD
Associate Editor, Communications Earth & Environment
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Summary

Jakobsson et al. present new bathymetry and CTD data to show that Atlantic water likely flows into Victoria Fjord and right up to the terminus of C. H. Ostenfeld. They hypothesize that this was likely responsible for the collapse of the ice tongue in the early 2000s. They supplement their main findings with additional data at the glacier terminus and make comparisons to glaciers in neighbouring fjords, where ice tongues still exist.

The authors provide new insight into the conditions of the fjord, the presence of Atlantic water and synthesis this with other datasets to make new conclusions about the role of Atlantic water into the fjord on ice tongues collapse, and the potential impact in the future. The study also provides new datasets for Victoria Fjord and C. H. Ostenfeld glacier which have been incorporated into Greenland wide datasets (BedMachine) which I assume makes these updates available to the wider community. These data will be of great interest to the wider community.

Comments

Overall, I found the paper generally good to read and the figures are appropriate. I do have some general comments (numbered below) and some more minor ones that are designed to improve the framing of the study, after which it will be a significant contribution to the field and an important additional piece of the puzzle towards us understanding of the role of Atlantic water in glacier dynamics in northern Greenland.

[1] My main thought when reading the paper was "Is this a paper about C. H. Ostenfeld or is it about all three of the glaciers with ice tongues in Northern Greenland?". The title and abstract suggest the former, but the rest of the manuscript (and the figures) gives as much weight to all three glaciers. For example, on line 75 the question posed suggests that the paper is trying to understand all three glaciers. I think the novelty of the paper is diluted because of this framing. The role of Atlantic Water and bathymetry of Petermann and Ryder Glaciers has already been presented in earlier publications (by many of the same authors). I strongly suggest bringing the new findings to the forefront of each section of the results/discussion and only giving space for about a paragraph of comparison to Petermann and Ryder, referring to previous papers where readers can find more in-depth information, rather than presenting this again here. Another option might be to have a single section that compares the new findings at C.H. Ostenfeld to Petermann and Ryder and in there discuss differences in sill bathymetry and the impact this likely had on C. H. Ostenfeld's tongue collapse versus the persistence of ice tongues at the other two glaciers.

[2] the data presented in this paper is novel, this fjord has not been surveyed before, nor the glacier ice front. However, the statement that Atlantic water reaches northern Greenland is supported by this data but has already been shown (by the authors themselves during their previous expeditions) to have made it into the fjords of northern Greenland. I suggest reframing this, in the same way as my comment [1] above, so the focus on Victoria Fjord and C. H. Ostenfeld itself, and the role of the bathymetry allowing that Atlantic Water to make it further into the fjord than neighbouring glaciers.

[3] Following on from above, because the paper appears to be focused on comparing all glaciers, rather than just presenting their new findings in Victoria Fjord, some of the data gets lost. For example, Fig. 2 it is very difficult to see the temperature data in the middle panel, which is arguably the main finding of the study and should be made larger. I also note that the profiles in the left panel of d) (note, I suggest that each panel should be separately labelled), are an exact replica of Fig. 5. in Jakobsson et al. 2020 Nature. This is not the first time this data has been presented, and that should be made clear to the reader with an explanation and reference to the previous paper. This is true for panels a) and b). The bathymetry data for Petermann and Ryder has already been presented and are collectively given more space on the page than the new data of C. H. Ostenfeld. A lot of the detailed bathymetry near the outer sill of Victoria Fjord is impossible to interpret in this small panel. I suggest revising the figure to bring the new data to the forefront (see suggestions in the minor comments).

[4] I'm not sure the Results and Discussion section includes enough Discussion. There is no synthesis between the timing of AW pulses and the collapse of the ice tongue and glacier dynamics for example. Nor is there any Discussion of the context of changes in Northern Greenland to any other region of the ice sheet/Arctic experiencing AW intrusions and associated glacier changes.

Minor comments

Line 36: It is my understanding that the format of Nature journal abstracts (or any abstract) should start with one or two sentences introducing the field. I suggest adding that before introducing the expedition or consider removing the details on the expedition entirely and leave just in the introduction.

Line 56: As above, the title and abstract are focused on C. H. Ostenfeld, but here you launch into giving details on Ryder Glacier first. That doesn't make sense. Reorder the paragraph so all background information is given on C. H. Ostenfeld first

and then put into wider context with neighbouring glaciers, for a couple of sentences only, referring to previous papers for details.

Line 67: “as observed satellite observations” needs revising.

Line 71: I don't see any reason for the detail on the crevasse at Petermann Glacier and the recent grounding line retreat. I suggest removing this detail or condensing this all to one background sentence on Petermann along the lines of: “two major calving events, grounding line retreat, but ice front advance since”.

Line 75: This research question does not mirror the information in the abstract and I found myself lost with what the main question of the paper actually is (see earlier comment). I suggest reframing this to be about C. H. Ostfeld, and the role of Atlantic Water in the ice tongue breakup, and supplement this later in the paper with a comparison to the neighbouring glaciers and the previous papers associated with data from their fjords.

Fig.1. Add reference to Koch paper in the caption. Figure would benefit from a scale bar so the reader can see the scale of the ice tongue collapse. Could add the length of the ice tongue prior to collapse in the caption as well.

Fig. 2. As mentioned above, I suggest this figure should be focused on C. H. Ostfeld. This could involve adding panels to highlight the outer sill region. I don't think the bathymetry for the other two fjords needs showing again, and instead the locations of the CTD measurements for Petermann and Ryder shown in Fig. 4. could be just added to a location map in the supplement. The temperature profile plot needs to be made larger, and each panel in d) needs labelling separately.

Line 158: I suggest not referring to Fig. 3 in this paragraph, make this about the bathymetry only and then merge any of the statements on geology into the following two paragraphs that start with the topic sentence on line 184 “Merging the bathymetry with geological maps...”. That provides the reader with nice context prior to any discussion of the geology.

Line 175: Can you compare these limited spot sounding measurements to what was known about the bathymetry from IBCAO? Do they agree or do they suggest that the fjord is deeper than previously thought?

Line 190: “similar sill influence” reads a bit awkwardly. I would suggest revising.

Fig. 4. The caption for panel b) is incomplete, it does not explain that the Atlantic water temperatures are shown on the right y axis, nor where the calculated 13-year lag times come from.

Line 233: Is any of the information in this paragraph new for this paper compared to the Jakobsson et al. 2020 paper? It seems like a summary. Again, this seems to come before discussing the impact of Atlantic water in Victoria Fjord, which comes in the following paragraph (Line 243). Discussion of Victoria Fjord should come first, as this is the novel part of this paper.

Line 262: This sentence saying there are peaks in temperature anomalies in 2004, 2005 and 2008 is a near duplicate on the one on line 252, I suggest combining the information to improve clarity.

Line 265: “non-floating” reads awkwardly, why not just “grounded”?

Line 270: units on Fig. 5. need to also be in “m above sea level” to match this statement.

Line 272: BedMachine version 5 is not referred to in the caption of Supplementary Figure 4. This needs revising because referring a reader to a Figure that doesn't show BedMachine doesn't make sense.

Line 320: See one of my main comments above, this paragraph does not mirror the title and abstract of the paper. I still feel the focus should be on C. H. Ostfeld and then make comparisons to previous work and other data for Petermann and Ryder.

Line 326: Arguably this is not a finding of this paper, we already knew the ice tongue collapsed. Also, it would be nice if the order of the conclusions reflected the order the information was presented in the manuscript, i.e. bathymetry first, especially as that and the temperature profiles are really the novel aspects of the paper.

Line 345: This is the first time this information has been presented, which is generally not recommended for conclusions. It needs to be mentioned in the Results section that warm water pulses in 2013 could reach the fjords in a few years' time.

Line 382: I suggest adding more detail about the oceanographic stations here, how many and where. Later add more detail on the XBTs as well, how many points and how were they distributed across the fjord.

Line 395: Why was this box to the west of Svalbard chosen. Add justification here.

Line 418: Was there ever a comparison made between the thickness recorded in the radar and the thickness in BedMachine?

Supplement:

Supplementary Figure 1: I don't see any real need for this Supplementary Figure 1. It also doesn't give any information on what imagery was used to map the front positions.

Supplementary Figure 5: Were there no images between 2002 and 2008? It's not clear otherwise why these images were selected to be shown. I suggest adding detail to the caption.

Reviewer #2 (Remarks to the Author):

Dear authors & editors,

This paper presents a number of new and exciting marine datasets – geophysical and oceanographic - from the C.H. Ostenfeld fjord in NW Greenland, an area that had never before been surveyed by a marine research vessel. The datasets would warrant publishing in their own right but the authors reach several interesting conclusions about the controls on Atlantic Water inflows to the glaciers of North Greenland plus their timing by comparing three NW Greenland fjords, and also about the calving styles being experienced by these last few ice tongues in Greenland. I happily recommend this paper for publication as it is well written and includes a series of clear and illustrative figures.

I can, however, make a few general suggestions; these are in addition to the ~40 comments in the attached PDF. In no particular order:

(1) The results and discussion are perhaps 2/3 to 1/3 split between the “ocean” datasets and AW story (bathymetry plus oceanography) and the calving regime shift (drone plus radar data) but this is not reflected in the abstract, which is focussed on the AW component. The last sentence of the abstract is also a bit misleading as it talks about future change in NW Greenland but this is not discussed in the text. What is really given is some awesome documentation of recent change at these N Greenland glaciers and their ice tongues. I understand the desire to make the study relevant to future change but perhaps then the authors should try to incorporate the argument about future change into their discussion? There must be projections of ice change/climate change that the authors could point to – in fact, I am fairly sure this group has done this work! The other way to do this might be to look back at Holocene (the authors own Petermann work) or LIG (models) changes at these glaciers as examples a bit further back of how these glaciers respond to climate change. (2) It is tempting to always want more (!) however, I did wonder whether the authors could really drive the AW inflow story home by doing some basic calculations of heat flux over the new bathymetry to the marine-terminating glacier faces? Through the channels in Figure 2d? Perhaps this would be nice semi-quantitative support to the bathymetric sill argument. (3) Working in Greenland myself I would encourage the authors to use Greenlandic placenames throughout, following: <https://nunataqqi.gl/>. (4) Some sentences seem overly long – which is OK if the reader is really paying attention, but perhaps breaking some of them up would make the read more enjoyable. (5) Check use of possessive hyphens and please add scalebars to the maps.

I am looking forward to seeing the manuscript published and I apologise to the authors for the length of time it took for me to submit my review.

Best wishes – Kelly Hogan

Reviewer #3 (Remarks to the Author):

Dear editor,

with high interest I have read the manuscript by Jakobsson et al. on the ocean heat impact on the CH Ostenfeld Glacier. I apologize for the delayed submission of the review. Glaciers in North Greenland and elsewhere show signs of retreat, often with knock-on effects on the amount of ice discharge relevant for sea level rise. The fjord system under investigation – Victoria Fjord – had previously been uncharted, and after the year 2000 the glacier appears to have disintegrated substantially. The author team work with a newly acquired, exiting, multidisciplinary dataset of bathymetry, hydrography and ice radar. The data sets are partly based highly innovative ways of acquisition, such as helicopter-based echo sounding and UAV based ice radar observations. One can only congratulate the authors for this achievement.

By comparison with the neighboring Petermann Glacier and Ryder Glacier, with the former showing some signs of retreat and the latter hardly any signs of retreat, the authors claim that the CH Ostenfeld Glacier (showing by comparison the strongest signs of retreat) is more exposed to subsurface warm water (referred to as Atlantic Water, AW). The authors claim, that the different sill heights provide different levels of shielding from AW, with Ryder Glacier being less exposed and CH Ostenfeld Glacier being most exposed. To my view, the connection of sill height and ocean temperatures below the sill is a solid finding and it is a novel one for the fjord system investigated. The authors imply that the geology in North Greenland is responsible for the presence of the sills in all 3 fjords they compare, and that the latter correspond to “resistant carbonate reefs belonging to the Silurian Washington Land Group”. I am not a geologist, and therefore I am not sure about the implications. I can't see from Fig. 3 where to find the Silurian Washington Land Group (is it the brownish/pinkish shading?). I also miss a statement whether the finding that the general geology in the area is affecting the sills is a surprise finding or whether this could be expected. Some more insights for non-geologists would be helpful.

The authors then claim the long-term warming of the water mass flowing into the Arctic via Fram Strait, and in specific warming events have led to the disintegration of the ice shelves. They claim that Atlantic Water temperature anomalies from Fram Strait take 13 years to circumnavigate the Arctic Ocean along the Eurasian and Canadian continental slope to arrive at Lincoln Sea where they affect submarine glacier melt. They use a hydrographic dataset from eastern Fram Strait going back to 1900 to claim AW in Fram Strait has reached a persistent plateau of high temperature after 2014, so that even warmer AW anomalies might be expected to arrive in Lincoln Sea in the next one or two years. While in general I agree that the Atlantic Water observed in Lincoln Sea originated from Fram Strait I find that this part of the analysis clearly lacks rigor, as follows.

1) The Fram Strait AW timeseries shown by the authors strongly deviates from mooring-based observations in the West Spitsbergen Current (WSC) after 1997. The latter neither shown the most prominent temperature peak of EN4 in 2000, nor do they show the persistent warm water plateau after 2014 (see McPherson et al., 2024; especially the supplemental material). There is a 2015-15 peak of warm water observed in the WSC, but massive cooling afterwards. In essence, the most prominent events in the EN4 time series may not be relevant in terms of inflow characteristics in the Atlantic Water in Fram Strait. It is a warning sign, that in the time period after 1997, where there is very good data coverage in Fram Strait, the EN4 data set fails to reproduce variability of Atlantic Water, as observed by year-round mooring-based observations in the West Spitsbergen Current. It is then even more doubtful that the EN4 data set can be trusted in terms of long-term trends going back to 1900 when there is essentially no data going into the EN4 dataset. In short, I strongly suggest not to base an analysis of the AW properties in the Arctic Ocean on the EN4 time series presented in the manuscript.

2) There is the recent finding, that the long-term warming of the AW in Fram Strait (WSC) has increased submarine melt of the Nioghalvfjærdsfjorden Glacier in Northeast Greenland (Wekerle et al., 2024). This supports the author's hypothesis, that change in the AW properties in Fram Strait may affect submarine glacier melt (with the caveat that Nioghalvfjærdsfjorden Glacier is rather close to the West Spitsbergen Current while Lincoln Sea is far away). At the same time, there is the finding the AW cooled strongly in Fram Strait after 2017 and that this strongly correlated to a cooling of AW on the shelf of Northeast Greenland, leading to a reduction of submarine melt of the Nioghalvfjærdsfjorden Glacier (McPherson et al., 2024). Thus it might be, that at least the 2014-17 warm water pulse observed in Fram Strait might arrive in some kind of modified form in Lincoln Sea at some point, but there is more complications for the authors' arguments (see next point).

3) The idea that the circulation in the Arctic Ocean works as some kind of clockwork, where more or less precisely after 13 years AW properties from Fram Strait appear in Lincoln Sea, is simplistic (too simplistic, in my view). There is a body of literature suggesting the AW flow to strongly correspond to the large-scale wind forcing (Körtke et al., 2012, Smith et al. 2022, Karcher et al., 2024). This affects both the speed of the circulation and the pathways that the AW takes on its way to North Greenland either via Canada Basin or via the mid-ocean ridges (e.g. Lomonosov Ridge). The temperature anomalies observed in Lincoln Sea almost presented in Fig. 4b (black dots) almost suggests a bimodal behaviour, either residing around 0.4°C or around 0.8°C. It is known that AW flowing toward Greenland via Lomonosov Ridge shows higher temperature (and salinity) than AW taking the long way via Canada Basin. What the authors find in terms of warm and cold events in Lincoln Sea (using the de Steur data points) might thus be AW arriving in Lincoln Sea from different origins.

I recommend a major revision of the oceanography in the manuscript. To me, all of the above suggests that the inferences on the large-scale connectivity of AW anomalies in the Arctic Ocean need more rigor to be convincing. This can be through the use of different data sets in Fram Strait (such as the WSC time series), an investigation of T/S properties in Lincoln Sea (there should be more than just the de Steur data) regarding the origins/pathways of the AW (Canada Basin vs Lomonosov Ridge), and via an improved integration with the literature regarding the temporal variability of the AW circulation in the Arctic Ocean.

Generally, the disintegration of the CH Osterfeld Glacier had already started before 1978, and it is not known when exactly this happened. This makes it difficult to establish a robust links between AW warming in Fram Strait and the disintegration. I think the authors should clearly acknowledge this. The title of the manuscript suggests the breakup can be linked to AW warming. I think it is fair to say that the authors provide plausible arguments base on the differential AW shielding of the 3 glaciers and the assumption that AW in the Arctic has somehow warmed. A direct cause and effect chain containing the timing of AW events and the timing of breakup sequences has not been established.

(Interestingly, the authors note in the early part of the manuscript that CH Osterfeld Glacier re-advanced in 2000/2001. Looking into the Wekerle et al. (2024) study, model simulations suggest that the late 1980s AW temperatures were quite low on the shelf of Northeast Greenland and thus in the WSC. A cold AW anomaly from the late 1980s in Fram Strait would be roughly a support of the 13 years time scale the authors put forward ...)

Detailed comments:

I 37: Clarify meaning of "accelerated"

I 45-46: I strongly suggest to skip this sentence (see main comment).

I 81-82: double usage of "first"

I 85: Clarify meaning of "chaotic"

I 96: Please note that the Barents Sea branch of AW cools down before leaving the Barents Sea, it is thus significantly colder than the Fram Strait branch. This means, for the central Arctic Ocean the Fram Strait branch is much more prominent in terms of heat supply. The authors might consider whether this information is relevant.

L 98: The whole point on the 12 years propagation time of AW has been addressed in my main comment. I find this part handwaving. If the authors really want to argue that the 12 years time is robust and meaningful, more evidence needs to be provided.

Fig. 2a: The use of different color bars for IBCAO and ship-based depth sounding is non-intuitive. It makes the map confusing to look at - at least from an oceanographic point of view. The hard transitions between IBCAO and ship-based

dataset mask everything else. It is not straightforward when looking at the maps to even tell easily where the sills are. This should be fixed. Inclusion of characteristic isobaths might help, too. An inclusion of a distance scale in the maps would also be useful, in order to judge the fjord widths.

Fig. 2 d: This manuscript investigates the impact of AW on CH Osterfeld Glacier breakup. The representation of the temperature profiles in a tiny panel wedged between the sill depth profiles makes the oceanography not very visible. Is it potential temperature? Please specify in the caption. For instance, can oceanographic information also be included in the maps, to support the author's arguments? Do we know anything about the circulation, have the authors acquired ocean currents e.g. with ADCPs? Such information would also help to visualize the fjord exchange flow.

I 168: Replace "greatly" by more specific information.

I 181: "more closely resembles ..." in the absence of an objective criteria for closeness I would leave this to the reader to decide. Skip or quantify closeness?

General comment: Reference 26/27 and 20/37 are identical. Dissolve duplication.

I 187: Is it a surprise finding, that the geology affects the presence of sills, or has this been shown many times, and it would be surprising not to find this? Please clarify.

I 201: I guess these are XBTs, as stated, and not XCTDs? Just out of curiosity: why was the choice made not to observe salinities?

I 235/36: I am not convinced. For any given temperature, the salinity near Ryder is higher than in the offshore profiles. Explain more precisely how, via mixing in the fjord, can those properties possibly be obtained. I suspect we rather see temporal variability here, with Ryder data from 2019 and Lincoln data from 2024. Please comment.

I 259-262: Regarding connectivity of AW between Fram Strait and Lincoln Sea, please see my major comments above.

I 261: "who recorded peak ..." is a repetition from I 251-52

I 267: shouldn't it be "contagious to"?

I 281: clarify term "bottom-out"

I 265-297: In my view the main point here is to establish that CH Osterfeld Glacier developed from an ice shelf into a tidewater glacier (main theme of the manuscript). This is convincingly done, and the data are spectacular – including the UAV based data. Yet, how relevant for the main theme is the inference, that possibly on seasonal timescales a small ice tongue may develop? How relevant is the finding, that not all of the glacier is grounded or nearly floating? Scientifically, these are intriguing findings, but maybe some of this should be reserved for a more specific publication. I find the paragraph not well-focussed, but of course I might miss something. I would recommend to sharpen the focus here (shorten the text) or at least to state more clearly, how the findings support the main message.

I 319-350: Most of the conclusion are fine, except for the last one. There is no such thing a persistent high temperatures in the WSC after 2014. The authors should acknowledge this. They should also clearly highlight that CH Osterfeld Glacier had already started to retreat before 1978, and it is not known when exactly this happened. This makes it difficult to establish a robust link between AW warming in Fram Strait and the disintegration. For the later part of the breakup, after 2001, when using a more robust time series of AW temperature in Fram Strait, this might be possible. Please add this to the conclusions.

I 390 CH Osterfeld Glacier had already started before 1978, and it is not known when exactly this happened. This makes it difficult to establish a robust links between AW warming in Fram Strait and the disintegration.

I 390-398: The AW temperature time series from EN4 data is not robust. It should not be used.

References referred to above (the authors should decide whether or not they want to include them)

Wekerle et al., Nat. Commun. 15, 1336 (2024).

McPherson et al., Science 385, 1360–1366 (2024)

Karcher, M., Smith, J. N., Kauker, F., Gerdes, R., & Smethie, W. M., Jr. (2012). Recent changes in Arctic Ocean circulation revealed by iodine-129 observations and modeling. *Journal of Geophysical Research*, 117(C8). <https://doi.org/10.1029/2011JC007513>

Smith, J. N., Smethie, W. M., Jr., & Casacuberta, N. (2022). Synoptic 129I and CFC-SF6 Transit Time Distribution (TTD) sections across the central Arctic Ocean from the 2015 GEOTRACES cruises. *Journal of Geophysical Research: Oceans*, 127(9). <https://doi.org/10.1029/2021JC018120>

Körtke, W., Walter, M., Huhn, O., Kanzow, T., & Rhein, M. (2024). Decadal changes in the pathways of the Atlantic water

core in the Arctic Ocean inferred from transient tracers. Journal of Geophysical Research: Oceans, 129, e2024JC021419.
<https://doi.org/10.1029/2024JC021419>

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Version 1:

Decision Letter:

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Dear Professor Jakobsson,

Your manuscript titled "Atlantic water access and the break-up of the C.H. Ostenfeld Gletsjer ice tongue, Northwest Greenland" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

Shin Sugiyama, PhD
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orcid.org/0000-0001-5323-9558

Nicola Colombo, PhD
Associate Editor, Communications Earth & Environment
Consulting Editor, Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

This is my second review of Jakobsson et al., which presents new data surveyed from Victoria Fjord in northern Greenland, and show, in the context of neighbouring glaciers, how the inner and outer sills impact the flow of warm Atlantic water to the terminus of C. H. Ostenfeld glacier.

I appreciate the author's efforts to address my previous comments. I found the paper indeed to be substantially improved, and I appreciate that they have brought the material on C. H. Ostenfeld to the front and centre of the manuscript, both in the text and the Figures. I am satisfied that the paper is suitable for publication now, subject to a few additional line comments I have included below. Note that the line numbers are related to the revised manuscript (not the tracked changes version).

Line comments:

Line 64: need a lead in statement here, e.g. "By comparison, the tongues of Ryder and Petermann Glacier's still extend 10s of km's along their fjords. In 1917 the Ryder ice tongue..." and then remove sentence starting "In contrast to..." on lines 67-68

Line 71: The grounding line sentence still feels out of place here given that you don't mention grounding line movement for the other two glaciers. I suggest removing or putting into better context.

Line 73: I appreciate the updated research question that does better frame the paper, but I'm not sure this a research question that you can answer in this paper? And is formulated as a general question rather than a testable hypothesis (see later comment for line 123)

Line 80: I'm not sure this paper explores "mechanisms controlling their stability" (e.g. actually calculating buttressing, or rifting/calving impacts) and rather only the impact of ocean conditions on ice tongue stability. Indeed, that's what the new first line of the abstract alludes to. Perhaps rephrase to that affect.

Line 85: "found a transformed fjord" suggests you surveyed it previously, before the ice tongue collapse. I suggest rephrasing.

Line 91: coincided

Line 93: Is Jakobshavn often referred to as an "ice stream". Consider adding the impact of ice tongue loss on inland thinning/ice speeds here as well.

Line 103: I don't see the need for this "back-of-the-envelope estimate", why not just present the "more comprehensive estimates"?

Line 123-124: So here you have the hypothesis you are testing in this paper? But this is not the same as the research question presented on line 73? In fact, Line 73 isn't the paper's research question but rather a more general question.

Line 156: consider changing “one third” to “first third”

Line 173: replace “is slightly more than” with “approximately”

Line 181: I assume this should be Fig. 2b?

Line 303: Is this the correct figures reference? Bed topography is not shown in Supplementary Fig. 4

Line 325: There are papers that have shown limited retreat after 2012 that you could cite here.

Line 355-358: I found this sentence a bit too long, consider splitting up or shortening.

Line 372: for the other two glaciers you have said “sill is like this, and tongue is like this” so I suggest doing the same on line 373, “doesn’t have a protective sill, has lost its ice tongue”

Reviewer #3 (Remarks to the Author):

Dear Editor,

I went through the rebuttal letter and the revised manuscript. The authors have accomplished a thorough revision, and my main concern (link to Fram Strait and the EN4 dataset) has been resolved, along with almost all of the remaining items that I put forward. Too bad to learn the ADCP data were not of much use due to low backscattering. I have come across similar situations. Thanks for also providing details on the salinity issue.

I think, now, all main conclusions are well-supported by the analyses provided. I'd like to congratulate the authors on this study, which I am sure will be received by the scientific community with great interest. I strongly support the publication in its current state. The study adds important knowledge on the theme of ocean-glacier interaction in Greenland, by exploring it in the often inaccessible Lincoln Sea area. To my view the manuscript can be published as is.

Cheers,

Torsten Kanzow

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Revision of (Original title): The Role of Atlantic water in the break-up of C.H. Ostenfeld Glacier's ice tongue, Northwest Greenland

Our replies are written in blue font, while comments from reviewers are kept in black.

Reviewer #1

Reviewer #1 provides constructive and helpful comments organised into four general points and several minor remarks. We thank the reviewer for their careful reading of the manuscript and address the points below.

General comments [1–3] raise a related overarching concern, namely that the novelty of the Victoria Fjord and C.H. Ostenfeld observations is diluted by excessive emphasis on comparisons with Ryder and Petermann glaciers and by the re-presentation of previously published data from those systems in the main figures. The reviewer also notes that while the presence of Atlantic Water in northern Greenland is not new, the novelty lies specifically in documenting its inflow into Victoria Fjord. More specific details regarding these points are also found in the minor comments.

We agree that the central contribution of this manuscript is the first unique oceanographic and bathymetric observations from Victoria Fjord and their implications for the collapse of the C.H. Ostenfeld ice tongue. We have therefore revised the manuscript throughout to bring these new results more clearly to the forefront.

Specifically:

- The research question (Line 75 in the reviewed version) has been reframed to focus explicitly on C.H. Ostenfeld Glacier.
- The Results and Discussion sections have been restructured so that Victoria Fjord observations lead each section, with comparison to Petermann and Ryder reduced to brief contextual paragraphs and references to previous publications.
- The discussion now more clearly emphasizes that while Atlantic Water presence in northern Greenland has been documented previously, the novel finding here is its direct penetration to the grounded margin in Victoria Fjord, facilitated by the absence of a shielding bathymetric sill.

- Figure 2 has been completely revised to focus solely on Victoria Fjord and C.H. Ostenfeld and showing the results in more detail, and the previous comparative figure has been moved to the Supplementary Material.
- Former Figure 4b has been removed, however, more a concern of Reviewer #3, and will therefore be addressed further below.

We believe these revisions clarify that this manuscript presents new observations from an unsurveyed fjord system and places the comparison with neighbouring glaciers in appropriate regional context without diluting the novelty. We thank Reviewer #1 making this point.

Comment [4] by Reviewer #1: “I’m not sure the Results and Discussion section includes enough Discussion. There is no synthesis between the timing of AW pulses and the collapse of the ice tongue and glacier dynamics for example. Nor is there any Discussion of the context of changes in Northern Greenland to any other region of the ice sheet/Arctic experiencing AW intrusions and associated glacier changes.”

In the revised manuscript, we have expanded the Discussion to provide clearer synthesis and broader context. In particular, we now place our findings in the framework of AW variability in northern Greenland and elsewhere in the Arctic, and discuss similarities and contrasts with other regions experiencing AW intrusions and associated glacier changes, more specifically comparing to 79N Glacier along with reference (See Reviewer #3).

With respect to the timing of AW pulses and the collapse of the ice tongue, we have taken care to avoid overinterpretation. While the revised manuscript discusses the potential influence of AW variability, we refrain from establishing a direct temporal cause-and-effect relationship, as the available data do not allow such linkage to be demonstrated robustly. We believe this approach provides a more balanced and rigorous treatment of the oceanographic forcing while maintaining the broader synthesis requested.

Line 36: It is my understanding that the format of Nature journal abstracts (or any abstract) should start with one or two sentences introducing the field. I suggest adding that before introducing the expedition or consider removing the details on the expedition entirely and leave just in the introduction.

We have added one sentence introducing the field, while removing the last sentence regarding the AW pulses and the future of North Greenland, as this has been downplayed only to briefly be touched upon in the discussion, considering also the comments of Rev. #3.

Line 56: As above, the title and abstract are focused on C. H. Ostenfeld, but here you launch into giving details on Ryder Glacier first. That doesn’t make sense. Reorder the paragraph so all background information is given on C. H. Ostenfeld first and then put into wider context with neighbouring glaciers, for a couple of sentences only, referring to previous papers for details.

We have reordered this and placed C.H. Ostenfeld first following the suggestion. Note that the previous Figure 2 is now moved to Supplementary material, in favour of a large display of all new data acquired in Victoria Fjord.

Line 67: “as observed satellite observations” needs revising.

Fixed

Line 71: I don’t see any reason for the detail on the crevasse at Petermann Glacier and the recent grounding line retreat. I suggest removing this detail or condensing this all to one background sentence on Petermann along the lines of: “two major calving events, grounding line retreat, but ice front advance since”.

We followed the suggestion and removed the sentence about the crevasse.

Line 75: This research question does not mirror the information in the abstract and I found myself lost with what the main question of the paper actually is (see earlier comment). I suggest reframing this to be about C. H. Ostenfeld, and the role of Atlantic Water in the ice tongue breakup, and supplement this later in the paper with a comparison to the neighbouring glaciers and the previous papers associated with data from their fjords.

We understand this point as mentioned above and have rephrased the question to directly be about C.H. Ostenfeld Glacier instead, and also revised the paragraph to further set the focus on the new data:

“Why did C.H Ostenfeld Glacier completely lose its ice tongue, whereas the neighbouring Ryder and Petermann glaciers have retained theirs, albeit in reduced size since 1917? Although these three glaciers are located within a few hundred kilometres of each other, their contrasting evolution suggests that factors beyond regional climate forcing must be considered. Resolving this question requires detailed knowledge of the glaciers’ environmental and oceanographic conditions, which have previously been unavailable from Victoria Fjord, where C.H. Ostenfeld Glacier drains. Ice tongues, depending on their configuration, may play an important role in stabilizing outlet glaciers due to their buttressing force and influence on calving¹²; therefore, understanding the mechanisms controlling their stability is essential for improved assessments of future sea-level rise¹³.”

Fig.1. Add reference to Koch paper in the caption. Figure would benefit from a scale bar so the reader can see the scale of the ice tongue collapse. Could add the length of the ice tongue prior to collapse in the caption as well.

Fixed, and length of ice tongue is now inferred on the map for clarity.

Fig. 2. As mentioned above, I suggest this figure should be focused on C. H. Ostenfeld. This could involve adding panels to highlight the outer sill region. I don’t think the bathymetry for the other two fjords needs showing again, and instead the locations of the CTD measurements for Petermann and Ryder shown in Fig. 4. could be just added to a location

map in the supplement. The temperature profile plot needs to be made larger, and each panel in d) needs labelling separately.

The figure has been revised following the Reviewer's suggestions. The previous version, which included all three glaciers, has been moved to the Supplementary Information, as we believe it provides useful comparative context and cannot be found in any previous publication since the Victoria Fjord/C.H. Ostenfeld Glacier data are presented here for the first time.

Line 158: I suggest not referring to Fig. 3 in this paragraph, make this about the bathymetry only and then merge any of the statements on geology into the following two paragraphs that start with the topic sentence on line 184 “Merging the bathymetry with geological maps...”. That provides the reader with nice context prior to any discussion of the geology.

We have followed this suggestion and revised the section so that the bathymetric description precedes the discussion of geology. Geological context has been consolidated into the subsequent paragraphs beginning with “When the bathymetry is merged with available geological maps, ...”. In addition, we have expanded the description of the seafloor morphology. We thank the reviewer for this helpful suggestion, which has improved the clarity of the section.

Line 175: Can you compare these limited spot sounding measurements to what was known about the bathymetry from IBCAO? Do they agree or do they suggest that the fjord is deeper than previously thought?

We follow this suggestion and compare the depth of the spot soundings with the Bedmachine, which in turn provided the bathymetry for IBCAO 5. This paragraph has been added:

“Comparing the spot soundings with IBCAO 5.0, which incorporates BedMachine data in previously unsurveyed areas such as Victoria Fjord, reveals large differences. The average depth difference is –342 m (IBCAO minus spot soundings), with a median difference of –361 m. The IBCAO/BedMachine bathymetry is systematically shallower in the central fjord and underestimates the maximum basin depth. The maximum observed difference amounts to –865 m. The large discrepancies are not unexpected. In previously unsurveyed fjords, BedMachine constrains seabed elevation, i.e. water depth, at the grounding line using ice thickness derived from radar data and a mass-conservation approach and interpolates fjord bathymetry by fitting a minimum-curvature surface, typically relying on sparse depth soundings located outside the fjord.”

Line 190: “similar sill influence” reads a bit awkwardly. I would suggest revising.

This is now revised to “In the following, we assess whether the oceanographic data from Victoria Fjord indicate that sill geometry similarly influences present conditions at C.H. Ostenfeld Glacier.”

Fig. 4. The caption for panel b) is incomplete, it does not explain that the Atlantic water temperatures are shown on the right y axis, nor where the calculated 13-year lag times come from.

We have removed Figure 4b considering the comments of Reviewer #3

Line 233: Is any of the information in this paragraph new for this paper compared to the Jakobsson et al. 2020 paper? It seems like a summary. Again, this seems to come before discussing the impact of Atlantic water in Victoria Fjord, which comes in the following paragraph (Line 243). Discussion of Victoria Fjord should come first, as this is the novel part of this paper.

The oceanographic conditions in the Lincoln Sea and Victoria Fjord are introduced earlier in the section (beginning at line 207 in the original manuscript), where we first describe the temperature structure and the newly acquired datasets, as well as AW intrusion and the role of bathymetry. We therefore consider that the discussion of Victoria Fjord precedes the comparative context. The opening paragraph of the Oceanography section describes that all datasets presented here are newly acquired in this study, including those from Victoria Fjord, the Lincoln Sea, and Petermann Fjord. The only previously published data are from inside Sherard Osborn Fjord, which was not revisited during the 2024 expedition. This is also stated in the first paragraph of the Oceanography section.

The new Figure 2, which focuses on the Lincoln Sea and Victoria Fjord, should, however, make it clear also here the Victoria Fjord is in focus.

Line 262: This sentence saying there are peaks in temperature anomalies in 2004, 2005 and 2008 is a near duplicate on the one on line 252, I suggest combining the information to improve clarity.

The entire section concerning Figure 4b in the original manuscript has been removed considering Reviewer #3, and therefore also the line 262.

Line 265: “non-floating” reads awkwardly, why not just “grounded”?

Fixed

Line 270: units on Fig. 5. need to also be in “m above sea level” to match this statement.

We have inferred in the main text that mean sea level is derived from the GGEOD 16, to make this clear:

“In C.H. Ostenfeld’s central sector, the margin is grounded at a depth of ~360 m and it rises to ~35 m above mean sea level (MSL, defined here relative to GEOID16³⁴; Fig. 5)”.

The figure caption has this information already, but we have made it clearer by including that the above mean sea level is equivalent to elevation: “UAV DEM is referenced to GGEOID16³⁴, with elevations expressed relative to the local mean sea level (MSL) datum.”

We have also changed the labels in Figure 5 to be consistent.

Line 272: BedMachine version 5 is not referred to in the caption of Supplementary Figure 4. This needs revising because referring a reader to a Figure that doesn’t show BedMachine doesn’t make sense.

Fixed, it is now referenced in the caption.

Line 320: See one of my main comments above, this paragraph does not mirror the title and abstract of the paper. I still feel the focus should be on C. H. Ostenfeld and then make comparisons to previous work and other data for Petermann and Ryder.

We have revised this to be aligned with a clearer focus on Victoria Fjord and C.H. Ostenfeld Glaciers. It now reads:

“Oceanographic and seafloor mapping data acquired during the GEOEO 2024 Expedition demonstrate that warm AW enters Victoria Fjord and reaches the margin of C.H. Ostenfeld Glacier. Placing these results in a regional context using new data from the Lincoln Sea and Petermann Fjord from the expedition, together with previously published observations from Sherard Osborn Fjord, allows us to further evaluate how geological and bathymetric controls regulate AW access to northern Greenland’s marine-terminating glaciers.”

Line 326: Arguably this is not a finding of this paper, we already knew the ice tongue collapsed. Also, it would be nice if the order of the conclusions reflected the order the information was presented in the manuscript, i.e. bathymetry first, especially as that and the temperature profiles are really the novel aspects of the paper.

We have reordered the conclusions so that they reflect the structure of the manuscript, with bathymetry, geology and temperature observations presented first, as these represent the primary new findings of this study. We have also clarified that the collapse of the C.H. Ostenfeld ice tongue itself is not a new observation; rather, the novel contribution of this paper lies in documenting the bathymetric configuration and direct oceanographic evidence of Atlantic Water reaching the glacier margin. While we retain a regional comparison to provide broader context, this is now clearly framed as supporting interpretation rather than the primary finding.

Line 345: This is the first time this information has been presented, which is generally not recommended for conclusions. It needs to be mentioned in the Results section that warm water pulses in 2013 could reach the fjords in a few years’ time.

We have removed this conclusion consider the comments of Reviewer #3.

Line 382: I suggest adding more detail about the oceanographic stations here, how many and where. Later add more detail on the XBTs as well, how many points and how were they distributed across the fjord.

This has been added: "In total, data from 38 CTD stations were acquired and 16 XBTs were launched from a helicopter. Two additional XBTs were deployed at CTD stations to compare the temperature profiles, which were found to align well. The XBTs in Victoria Fjord were distributed along the fjord to trace the water mass structure, with deployments at the glacier margins, including C.H. Ostenfeld Glacier and two locations at the margin of Harder Glacier."

Line 395: Why was this box to the west of Svalbard chosen. Add justification here.

This part has been removed from the manuscript in light of the comments from Reviewer #3.

Line 418: Was there ever a comparison made between the thickness recorded in the radar and the thickness in BedMachine?

We have not undertaken a systematic comparison between the RES-derived thickness and BedMachine as part of this study. While localized differences are apparent (Supplementary Fig. 6), a detailed quantitative assessment is beyond the scope of the present manuscript and will be addressed in future work.

Supplement:

Supplementary Figure 1: I don't see any real need for this Supplementary Figure 1. It also doesn't give any information on what imagery was used to map the front positions.

We have moved Supplementary Figure 1 to follow the Supplementary figure showing the full image series of C.H. Ostenfeld, so that it serves as a visual reference for the former extent and geometry of the ice tongue. We consider this contextual overview helpful for readers when interpreting the regime shift described in the manuscript, and therefore prefer to retain it.

Supplementary Figure 5: Were there no images between 2002 and 2008? It's not clear otherwise why these images were selected to be shown. I suggest adding detail to the caption.

We thank the reviewer for this comment. Landsat imagery from 2003 onward is affected by scan-line corrector failure, resulting in striping artifacts. This is visible in the 2008–2012 images and was the reason only a limited number of scenes from this period were initially included.

However, we agree that illustrating the rapid break-up phase more clearly strengthens the presentation. We have therefore added an image from 2003 that captures the onset of rapid disintegration, as well as an enlarged 1999 image showing the full extent of the longer ice tongue prior to collapse, and a full-length image from 2002. We believe this revised sequence provides a clearer and more complete overview of the evolution of the ice tongue.

The caption has been expanded: “Figure 2. Landsat images of the C.H. Ostenfeld Glacier showing the break-up and evolution of the ice tongue from 1999 to 2024 at selected snapshots in time. Panels a-j correspond to images from 1999-07-23, 2002-07-31, 2003-07-24, 2008-07-30, 2010-07-28, 2012-07-20, 2016-08-27, 2019-07-30, 2024-05-20, and 2024-08-17. The ice margin from 17 August 2024 is shown in white as a reference in all images, while the margin at the time of each image is shown in blue. Grounding-line positions inferred from radio-echo sounding profiles are indicated by orange-filled circles. The names of the glaciers are shown only in (a). Panels i and j show the full longitudinal extent of the ice tongue prior to and during the main break-up phase, allowing comparison with its later reduced state. By 2003, only a few kilometres of floating ice tongue remained attached to the outlet glacier. The stripes in panels e-h are due to errors from the Scan Line Corrector in Landsat-7 data.”

Reviewer #2 (Remarks to the Author):

Dear authors & editors,

This paper presents a number of new and exciting marine datasets – geophysical and oceanographic - from the C.H. Ostenfeld fjord in NW Greenland, an area that had never before been surveyed by a marine research vessel. The datasets would warrant publishing in their own right but the authors reach several interesting conclusions about the controls on Atlantic Water inflows to the glaciers of North Greenland plus their timing by comparing three NW Greenland fjords, and also about the calving styles being experienced by these last few ice tongues in Greenland. I happily recommend this paper for publication as it is well written and includes a series of clear and illustrative figures.

I can, however, make a few general suggestions; these are in addition to the ~40 comments in the attached PDF. In no particular order:

(1) The results and discussion are perhaps 2/3 to 1/3 split between the “ocean” datasets and AW story (bathymetry plus oceanography) and the calving regime shift (drone plus radar data) but this is not reflected in the abstract, which is focussed on the AW component. The last sentence of the abstract is also a bit misleading as it talks about future change in NW Greenland but this is not discussed in the text. What is really given is some awesome documentation of recent change at these N Greenland glaciers and their ice tongues. I understand the desire to make the study relevant to future change but perhaps then the authors should try to incorporate the argument about future change into their discussion?

There must be projections of ice change/climate change that the authors could point to – in fact, I am fairly sure this group has done this work! The other way to do this might be to look back at Holocene (the authors own Petermann work) or LIG (models) changes at these glaciers as examples a bit further back of how these glaciers respond to climate change.

We thank the reviewer for these constructive comments. In the revised manuscript, we have removed the forward-looking statements regarding future AW influx together with the EN4-based analysis, as these data were found not to be robust enough (complaints from Reviewer #3). Since the abstract is so short there is not room for much more, but it has been revised by removing the last sentence on the AW warm pulses, and a new first sentence has been added to set the scene and draw the attention to ice ocean interaction at the north Greenland outlet glaciers.

(2) It is tempting to always want more (!) however, I did wonder whether the authors could really drive the AW inflow story home by doing some basic calculations of heat flux over the new bathymetry to the marine-terminating glacier faces? Through the channels in Figure 2d? Perhaps this would be nice semi-quantitative support to the bathymetric sill argument.

A quantitative estimate of heat flux through the bathymetric channels would indeed provide additional constraints on the potential oceanic influence at the glacier fronts. However, such calculations would require assumptions about velocity structure and exchange flow that are not sufficiently constrained by the available observations, particularly in the absence of reliable current measurements, and the fact that we only could enter the outer part of Victoria Fjord with IB Oden to collect data.

In the revised manuscript, we have put more emphasis on the analysis on the new bathymetric and hydrographic observations from Victoria Fjord and have avoided extending the interpretation beyond what can be robustly supported by the data. We therefore consider a semi-quantitative heat-flux estimate to be beyond the scope of the present study. We agree that this would be an interesting avenue for future work.

(3) Working in Greenland myself I would encourage the authors to use Greenlandic placenames throughout, following: <https://nunataqqi.gl/>.

We are grateful for this reminder. We have gone through and changed all names in accordance with the Nunataqqi.gl. This means that the glaciers are now gletsjers, and the maps have also been updated.

(4) Some sentences seem overly long – which is OK if the reader is really paying attention, but perhaps breaking some of them up would make the read more enjoyable.

We have gone through the manuscript broken up the longest sentences to improve readability.

(5) Check use of possessive hyphens and please add scalebars to the maps.

We have carefully checked the manuscript for consistency in possessive forms and hyphenation and corrected minor inconsistencies where needed. The major change inferred is that we followed the recommendation and, for example, write the C.H. Ostenfeld Gletsjer ice tongue, instead of C.H. Ostenfeld's ice tongue. Scale bars have been added to all maps, except for the smallest-scale overview maps in Figures 1a, where the latitude–longitude graticules provide sufficient information on spatial scale.

I am looking forward to seeing the manuscript published and I apologise to the authors for the length of time it took for me to submit my review.

Thanks!

We have also gone through the minor comments in the marked-up manuscript and inferred corrections accordingly. We list the very few where we have not followed the suggestions fully.

- We have not updated the satellite image in Figure 1 to one from 2025, since we prefer to keep the 2024 as it represents the time of the GEOEO 2024 expedition, which provides information on the ice situation in the fjord.
- We have not used the 2015 CTD data in addition to the 2024 from Petermann Fjord, while the difference is small, it does not add to the interpretation.

Reviewer #3 (Remarks to the Author):

Dear editor,

with high interest I have read the manuscript by Jakobsson et al. on the ocean heat impact on the CH Ostenfeld Glacier. I apologize for the delayed submission of the review. Glaciers in North Greenland and elsewhere show signs of retreat, often with knock-on effects on the amount of ice discharge relevant for sea level rise. The fjord system under investigation – Victoria Fjord – had previously been uncharted, and after the year 2000 the glacier appears to have disintegrated substantially. The author team work with a newly acquired, exiting, multidisciplinary dataset of bathymetry, hydrography and ice radar. The data sets are partly based highly innovative ways of acquisition, such as helicopter-based echo sounding and UAV based ice radar observations. One can only congratulate the authors for this achievement.

By comparison with the neighboring Petermann Glacier and Ryder Glacier, with the former showing some signs of retreat and the latter hardly any signs of retreat, the authors claim that the CH Ostenfeld Glacier (showing by comparison the strongest signs of retreat) is more exposed to subsurface warm water (referred to as Atlantic Water, AW). The authors claim, that the different sill heights provide different levels of shielding from AW, with Ryder Glacier being less exposed and CH Ostenfeld Glacier being most exposed. To my view, the connection of sill height and ocean temperatures below the sill is a solid finding and it is a novel one for the fjord system investigated.

We thank the reviewer for this very positive assessment of the manuscript.

The authors imply that the geology in North Greenland is responsible for the presence of the sills in all 3 fjords they compare, and that the latter correspond to “resistant carbonate reefs belonging to the Silurian Washington Land Group”. I am not a geologist, and therefore I am not sure about the implications. I can’t see from Fig. 3 where to find the Silurian Washington Land Group (is it the brownish/pinkish shading?). I also miss a statement whether the finding that the general geology in the area is affecting the sills is a surprise finding or whether this could be expected. Some more insights for non-geologists would be helpful.

Thanks for this comment. In the revised manuscript, we have expanded and clarified the geological description to make it more accessible to a broader readership and to better explain the relationship between bedrock geology and sill formation.

For example, we now explicitly describe why the carbonate reefs form sills:

“The inner sill in Victoria Fjord corresponds to a belt of carbonate reefs belonging to the Silurian Washington Land Group that form a former shelf edge^{25,26} (Fig 3). These reefs are dolomitized and silicified, making them less likely to be eroded away, which leads to topographic highs on land and sills in the fjords. The same bedrock forms the base of a shallow inner sill that nearly continuously extends across Sherard Osborn Fjord and greatly restricts the inflow of AW²¹.”

In addition, we have added labels indicating the inner and outer sills in Figure 3 and included the following clarification in the caption: “Dashed line marks approximate position of the Washington Land Group”.

The new bathymetric data, including the gridded helicopter soundings, allow us for the first time to directly demonstrate a connection between the sills in Victoria Fjord and the underlying bedrock geology. While such a relationship is not unexpected and has often been hypothesized in our own proposals leading up to the GEOEO24 expedition, it has not previously been clearly documented for the sills in Sherard Osborn Fjord and Petermann Fjord. In many regions, the bedrock geology is more structurally complex; in contrast, here in the northern Greenland the geological units occur in relatively simple belts oriented perpendicular to the fjords, which makes the relationship particularly evident.

Overall, the revisions made in response to Reviewer #1, specifically the restructuring, have strengthened the geological context and clarified the significance of this finding.

The authors then claim the long-term warming of the water mass flowing into the Arctic via Fram Strait, and in specific warming events have led to the disintegration of the ice shelves. They claim that Atlantic Water temperature anomalies from Fram Strait take 13 years to circumnavigate the Arctic Ocean along the Eurasian and Canadian continental slope to arrive at Lincoln Sea where they affect submarine glacier melt. They use a hydrographic dataset from eastern Fram Strait going back to 1900 to claim AW in Fram Strait has reached a persistent plateau of high temperature after 2014, so that even warmer AW anomalies might be expected to arrive in Lincoln Sea in the next one or two years. While in general I

agree that the Atlantic Water observed in Lincoln Sea originated from Fram Strait I find that this part of the analysis clearly lacks rigor, as follows.

1) The Fram Strait AW timeseries shown by the authors strongly deviates from mooring-based observations in the West Spitsbergen Current (WSC) after 1997. The latter neither shown the most prominent temperature peak of EN4 in 2000, nor do they show the persistent warm water plateau after 2014 (see McPherson et al., 2024; especially the supplemental material). There is a 2015-15 peak of warm water observed in the WSC, but massive cooling afterwards. In essence, the most prominent events in the EN4 time series may not be relevant in terms of inflow characteristics in the Atlantic Water in Fram Strait. It is a warning sign, that in the time period after 1997, where there is very good data coverage in Fram Strait, the EN4 data set fails to reproduce variability of Atlantic Water, as observed by year-round mooring-based observations in the West Spitsbergen Current. It is then even more doubtful that the EN4 data set can be trusted in terms of long-term trends going back to 1900 when there is essentially no data going into the EN4 dataset. In short, I strongly suggest not to base an analysis of the AW properties in the Arctic Ocean on the EN4 time series presented in the manuscript.

We thank the reviewer for this careful and constructive assessment of the Atlantic Water (AW) analysis based on EN4.

The reviewer raises an important concern regarding the representation of AW variability in eastern Fram Strait by the EN4 dataset. We agree that the discrepancies between EN4 and mooring-based observations call into question the reliability of EN4 for resolving detailed inflow characteristics and variability of AW in Fram Strait. We also agree with the reviewer that if EN4 does not reproduce AW variability robustly during the modern observational era, it is difficult to justify using it to infer long-term trends extending back to 1900, when observational constraints were sparse.

Our intention in including the EN4 time series was to illustrate long-term trends in the Arctic AW, and to discuss the possibility of an upstream–downstream connection between AW temperature variability in Fram Strait and Lincoln Sea. Such connections are physically plausible and have been demonstrated at shorter lags in other sectors of the Arctic inflow pathway (e.g., Svinøy–Fram Strait, ~1–2 years; Fram Strait–Nioghalvfjærdsfjord, ~3 years). However, we agree that the present EN4-based analysis does not provide a sufficiently rigorous basis for drawing conclusions about long-term trends, multi-decadal variability or forecasting the arrival of anomalies in the Lincoln Sea. Considering the more long-term warming trend of the Arctic AW during the 20th century, we now only refer to the observational compilations presented in Polyakov et al. (2004) and Skagseth et al. (2008) in this discussion

Considering the reviewer's comments, we have removed the EN4-based analysis of Fram Strait AW variability from the revised manuscript. We now limit our discussion to well-documented aspects of Atlantic Water propagation and clearly distinguish between established observational evidence and more speculative upstream connections.

The following paragraph is hence removed in the revised version:

“Data on AW temperature extracted from west of Svalbard (77–80°N/0–10°E), extending back to 1900 (see Methods), reveal a general warming trend (Fig. 4b). Warmer pulses began to emerge after 1930, intensified from 1991, and developed into a more coherent, prolonged warm pulse after around 2014. The core of the AW in the central Arctic Ocean lies at a depth of about 200–400 meters 18. As previously mentioned, a rough estimation yields that the AW pulses will reach the Lincoln Sea at around 12 years after entering the Arctic Ocean through the Fram Strait. This timing aligns well with observations made in the north western Lincoln Sea by de Steur et al 33, who recorded peaks of AW temperature in 2004, 2005 and 2008, potentially linked to a series of warm AW pulses that entered the Arctic Ocean some 10–15 years earlier (Fig. 4b).”

We believe that this revision strengthens the manuscript by avoiding overinterpretation of a data product that may not adequately resolve AW variability in Fram Strait.

2) There is the recent finding, that the long-term warming of the AW in Fram Strait (WSC) has increased submarine melt of the Nioghalvfjordsfjorden Glacier in Northeast Greenland (Wekerle et al., 2024). This supports the author’s hypothesis, that change in the AW properties in Fram Strait may affect submarine glacier melt (with the caveat that Nioghalvfjordsfjorden Glacier is rather close to the West Spitsbergen Current while Lincoln Sea is far away). At the same time, there is the finding the AW cooled strongly in Fram Strait after 2017 and that this strongly correlated to a cooling of AW on the shelf of Northeast Greenland, leading to a reduction of submarine melt of the Nioghalvfjordsfjorden Glacier (McPherson et al., 2024). Thus it might be, that at least the 2014–17 warm water pulse observed in Fram Strait might arrive in some kind of modified form in Lincoln Sea at some point, but there is more complications for the authors’ arguments (see next point).

We thank the reviewer for highlighting these recent studies. We have incorporated reference to Wekerle et al. (2024) as well as McPherson (2024) in the final paragraph of the oceanography section to illustrate that relatively modest variations in AW temperature linked to Fram Strait variability can influence submarine melt rates in Northeast Greenland. At the same time, we avoid extending this comparison too far, as the oceanographic setting of the Lincoln Sea differs substantially from that of Nioghalvfjordsfjorden Glacier.

We have also clarified in the text that while AW variability may influence glacier–ocean interactions, the propagation and modification of specific warm pulses toward the Lincoln Sea remain uncertain. Our aim is therefore to provide context without implying a direct or temporally resolved linkage between Fram Strait variability and conditions in Victoria Fjord. The following has been added:

“Corresponding measurements of AW in the Southern Lincoln Sea, closer to Victoria Fjord, are lacking. It therefore remains uncertain whether the anomalously warm AW (~0.8 °C) observed on Northern Lincoln Sea continental slope occasionally reached Victoria Fjord in the past. Nevertheless, the documented spatial and temporal variability of AW in the Lincoln Sea indicates that episodic warming cannot be excluded. On the Northeast Coast of

Greenland, interannual variability in basal melt of 79N Glacier has been shown to correlate with changes in AW temperature, demonstrating that relatively modest AW variability can influence glacier–ocean interactions elsewhere in Greenland (Wekerle et al. 2024). Recent observations also indicate that cooling of AW in Fram Strait can reduce submarine melt in Northeast Greenland, highlighting the sensitivity of glacier–ocean interactions to upstream AW variability (McPherson, 2024)”

3) The idea that the circulation in the Arctic Ocean works as some kind of clockwork, where more or less precisely after 13 years AW properties from Fram Strait appear in Lincoln Sea, is simplistic (too simplistic, in my view). There is a body of literature suggesting the AW flow to strongly correspond to the large-scale wind forcing (Körtke et al., 2012, Smith et al. 2022, Karcher et al., 2024). This affects both the speed of the circulation and the pathways that the AW takes on its way to North Greenland either via Canada Basin or via the mid-ocean ridges (e.g. Lomonosov Ridge). The temperature anomalies observed in Lincoln Sea almost presented in Fig. 4b (black dots) almost suggests a bimodal behaviour, either residing around 0.4°C or around 0.8°C. It is known that AW flowing toward Greenland via Lomonosov Ridge shows higher temperature (and salinity) than AW taking the long way via Canada Basin. What the authors find in terms of warm and cold events in Lincoln Sea (using the de Steur data points) might thus be AW arriving in Lincoln Sea from different origins.

We thank the reviewer for this relevant comment. We fully acknowledge that AW circulation pathways and associated transit times are complex and modulated by large-scale wind forcing and circulation variability. We agree that our wording was over-simplified and giving the impression of AW propagation as a quasi-deterministic “clockwork” system with a~13-year transit time.

In response, we have replaced

"This journey takes about 12 years from the Fram Strait, using an average flow speed of 0.02 ms⁻¹ [refs 18,19]

with

" This journey would take approximately 12 years from the Fram Strait, assuming a mean flow speed of 0.02 m s⁻¹ along the continental margin. However, this back-of-the-envelope estimate is highly simplified, as it neglects variability in the circulation pathway, recirculation, eddy-driven transport, and temporal changes in AW flow strength. More comprehensive estimates based on observed AW signal propagation suggest a mean transit time from the Fram Strait to the Lincoln Sea of ~10–15 years, with variability arising from intrinsic eddy activity as well as large-scale wind-driven fluctuations in the boundary current [references: Körtke et al., 2012, Smith et al. 2022, Karcher et al., 2024 + (18) and (19) in the submitted manuscripts]"

Furthermore, we have updated Figure 1 to show the broader range of AW transit time from the Fram Strait to the Lincoln Sea.

We find the reviewer's suggestion compelling that the apparent bimodal structure of the Lincoln Sea temperature observations (Fig. 4b; de Steur data points) may reflect the arrival of AW from different upstream branches. In the revised ms, we include in the discussion the possibility that variability in the Lincoln Sea record may reflect shifting dominance between different AW branches. We have revised the MS to include the following:

“These measurements cover the period 1991–2009, with a data gap between 1997 and 2002, and reveal temporal as well as spatial variability, including a noticeable bi-modal pattern with particularly high AW temperatures in 2004, 2005 and 2008. The apparent bi-modal variability of AW temperatures in the Lincoln Sea may reflect variability in upstream circulation pathways, with warmer anomalies potentially associated with AW advected along the Lomonosov Ridge.”

I recommend a major revision of the oceanography in the manuscript. To me, all of the above suggests that the inferences on the large-scale connectivity of AW anomalies in the Arctic Ocean need more rigor to be convincing. This can be through the use of different data sets in Fram Strait (such as the WSC time series), an investigation of T/S properties in Lincoln Sea (there should be more than just the de Steur data) regarding the origins/pathways of the AW (Canada Basin vs Lomonosov Ridge), and via an improved integration with the literature regarding the temporal variability of the AW circulation in the Arctic Ocean.

We thank the reviewer for this thorough and constructive evaluation of the oceanographic framing in the manuscript.

We agree that the previous version did not provide sufficient rigor to support the inferences made regarding large-scale connectivity of Atlantic Water (AW) anomalies across the Arctic Ocean. In particular, the linkage between Fram Strait variability and Lincoln Sea conditions relied on limited observational constraints and may have led to overinterpretation, even if we only had a short paragraph on this topic with reference to Figure 4b.

In light of these comments, we have revised the manuscript and removed the upstream connectivity analysis linking Fram Strait variability to Lincoln Sea conditions shown in Figure 4b. We agree that a robust assessment of such connectivity would require incorporation of additional datasets (e.g., the WSC time series), a more detailed investigation of T/S properties in the Lincoln Sea, and a deeper integration with the literature on AW pathway variability, which is beyond the scope of the present study.

We have, also considering Reviewer #1 comments, placed more emphasis on the new Victoria Fjord data, and believe that this improves the rigor and balance of the manuscript and prevents overinterpretation of limited upstream constraints. The revised manuscript therefore focuses on regional observations that are directly supported by our data, while avoiding conclusions about basin-scale connectivity that cannot be firmly constrained.

Generally, the disintegration of the CH Ostenfeld Glacier had already started before 1978, and it is not known when exactly this happened. This makes it difficult to establish a robust links between AW warming in Fram Strait and the disintegration. I think the authors should clearly acknowledge this.

With all revisions we now have made, specifically by removing figure 4b, it should now be clear that we do not claim to have a timed link between AW in the Fram Strait and the collapse of C.H. Ostenfeld Glacier.

The title of the manuscript suggests the breakup can be linked to AW warming. I think it is fair to say that the authors provide plausible arguments base on the differential AW shielding of the 3 glaciers and the assumption that AW in the Arctic has somehow warmed. A direct cause and effect chain containing the timing of AW events and the timing of breakup sequences has not been established.

We thank the reviewer for this thoughtful comment regarding the framing of our conclusions. We agree that the original title could be interpreted as implying a direct causal link between AW warming and the breakup of C.H. Ostenfeld Glacier's ice tongue, including a resolved temporal cause-and-effect relationship. As the reviewer correctly notes, such a direct timing link between specific AW anomalies and the breakup sequence has not been established.

Our intention was to highlight the potential influence of differential AW access on ice tongue stability, rather than to claim a documented event-scale causal chain. To better reflect the scope of the evidence presented, we have revised the title to:

“Atlantic water access and the break-up of the C.H. Ostenfeld Glacier ice tongue, Northwest Greenland”

This revised title more accurately conveys that our study focuses on AW access and its potential influence on ice tongue stability, without implying a demonstrated direct causal trigger. In addition, we have clarified the discussion to explicitly state that while the observations support a plausible oceanic influence, they do not establish a precise temporal cause-and-effect relationship between AW variability and breakup events.

(Interestingly, the authors note in the early part of the manuscript that CH Ostenfeld Glacier re-advanced in 2000/2001. Looking into the Wekerle et al. (2024) study, model simulations suggest that the late 1980s AW temperatures were quite low on the shelf of Northeast Greenland and thus in the WSC. A cold AW anomaly from the late 1980s in Fram Strait would be roughly a support of the 13 years time scale the authors put forward ...)

See our reply to major comment 2).

Detailed comments:

I 37: Clarify meaning of “accelerated”

Fixed: We changed it to “rapid”. We used “accelerated” as one could already see signs of the break-up in form of increased fragmentation before 2002.

I 45-46: I strongly suggest to skip this sentence (see main comment).

Fixed: The last sentence is removed.

I 81-82: double usage of “first”

Fixed, we settled with stating that the expedition was the first to reach the fjord.

I 85: Clarify meaning of “chaotic”

Fixed: Chaotic is not really needed, so we removed the word.

I 96: Please note that the Barents Sea branch of AW cools down before leaving the Barents Sea, it is thus significantly colder than the Fram Strait branch. This means, for the central Arctic Ocean the Fram Strait branch is much more prominent in terms of heat supply. The authors might consider whether this information is relevant.

Fixed: We added a sentence stating this.

“The AW flows into the central Arctic Ocean via two major branches, through the Fram Strait and across the Barents Sea 18, with the former dominating the heat transport into the central Arctic Ocean, as the latter cools significantly along its path across the Barents Sea.”

L 98: The whole point on the 12 years propagation time of AW has been addressed in my main comment. I find this part handwaving. If the authors really want to argue that the 12 years time is robust and meaningful, more evidence needs to be provided.

Fixed: We have addressed the main comment above.

Fig. 2a: The use of different color bars for IBCAO and ship-based depth sounding is non-intuitive. It makes the map confusing to look at - at least from an oceanographic point of view. The hard transitions between IBCAO and ship-based dataset mask everything else. It is not straightforward when looking at the maps to even tell easily where the sills are. This should be fixed. Inclusion of characteristic isobaths might help, too. An inclusion of a distance scale in the maps would also be useful, in order to judge the fjord widths.

We thank the reviewer for this helpful suggestion. Figure 2 has been revised and enlarged substantially in response to Reviewer #1, which improves the clarity of the bathymetric structure and makes the sill locations more readily identifiable. We have retained separate colour scales for the IBCAO background and the ship-based bathymetry, as this distinction clearly highlights the newly acquired high-resolution data relative to the existing compilation. However, the larger figure size and improved layout reduce the visual impact of the transition between the datasets. We explored the inclusion of characteristic isobaths, but found that they cluttered the figure and reduced overall readability given the already dense information content. We have, however, added scale bars to facilitate assessment of fjord widths.

Fig. 2 d: This manuscript investigates the impact of AW on CH Ostenfeld Glacier breakup. The representation of the temperature profiles in a tiny panel wedged between the sill depth profiles makes the oceanography not very visible. Is it potential temperature? Please specify in the caption. For instance, can oceanographic information also be included in the maps, to support the author's arguments? Do we know anything about the circulation, have the authors acquired ocean currents e.g. with ADCPs? Such information would also help to visualize the fjord exchange flow.

In the new Figure 2 the panel showing temperature profiles (now panel c) has been enlarged substantially to improve visibility, and it only shows profiles from Victoria Fjord and Lincoln Sea, as these profiles are central to our interpretation, we have made them the primary focus of the figure. The temperature shown is potential temperature, and this has now been clarified in the caption as well as the figure.

Regarding circulation, we did acquire ADCP data during the expedition. However, the data quality from Victoria Fjord was not sufficient for straightforward interpretation of the exchange flow. We attribute this to exceptionally clear water conditions, which reduce acoustic backscatter and are a known limitation for ADCP measurements in Arctic environments. For this reason, we have not included the ADCP data in the present ms.

I 168: Replace “greatly” by more specific information.

Fixed: “The same bedrock forms the base of a shallow inner sill that nearly continuously extends across Sherard Osborn Fjord and greatly restricts the inflow of AW, as evidenced by a decrease in AW temperature of approximately 0.2 °C landward of the sill 24 (Supplementary Fig. 1d).”

I 181: “more closely resembles ...” in the absence of an objective criteria for closeness I would leave this to the reader to decide. Skip or quantify closeness?

As this is important information, we have instead of removing the sentence described the resemblance a bit more. “The bathymetric profile across the sill at the mouth of Petermann Fjord is similar in overall geometry to that of the inner sill in Victoria Fjord, with

comparable cross-sectional shape, although the deepest passage is located to the west rather than the east (Supplementary Fig. 1)."

General comment: Reference 26/27 and 20/37 are identical. Dissolve duplication.

Fixed.

I 187: Is it a surprise finding, that the geology affects the presence of sills, or has this been shown many times, and it would be surprising not to find this? Please clarify.

The geology has been expanded, and this should be clear in the revised manuscript.

I 201: I guess these are XBTs, as stated, and not XCTDs? Just out of curiosity: why was the choice made not to observe salinities?

The entire helicopter dropping of probes was not in the original plan, and hence no XCTDs were purchased. The plan was to reach into the fjord and take CTDs with the ship, but the massive amount of icebergs prevented this. So, we came up with the helicopter option of getting some data in the ice-loaded fjord during the expedition, and used the available XBTs, which had been stocked to regularly calibrate the multibeam. We would very much have liked to have XCTDs!

I 235/36: I am not convinced. For any given temperature, the salinity near Ryder is higher than in the offshore profiles. Explain more precisely how, via mixing in the fjord, can those properties possibly be obtained. I suspect we rather see temporal variability here, with Ryder data from 2019 and Lincoln data from 2024. Please comment.

We agree that this point was not clearly formulated, and the statement "the water below the sill in the inner basin of Sherard Osborn Fjord is both colder and fresher than the AW outside the fjord in the Lincoln Sea" -- while correct -- is quite difficult to conclude from Figures 2d and 4a alone. This fact is, however, easy to appreciate by inspecting Fig. 2 in Jakobsson et al. (2020), which shows vertical temperature and salinity profiles in the Sherard Osborn Fjord and in the Lincoln Sea taken in 2019: here it is evident that the water inside the inner sill, below around 300 m, are fresher and colder than water at similar depths found in the outer part of the fjord and the Lincoln Sea. Without having the additional information of the vertical salinity distribution, the statement in the text is ambiguous, and as the reviewer suggests Fig 4a could be interpreted as "that for any given temperature, the salinity near Ryder is higher than in the offshore profiles."

To address this issue, we have changed

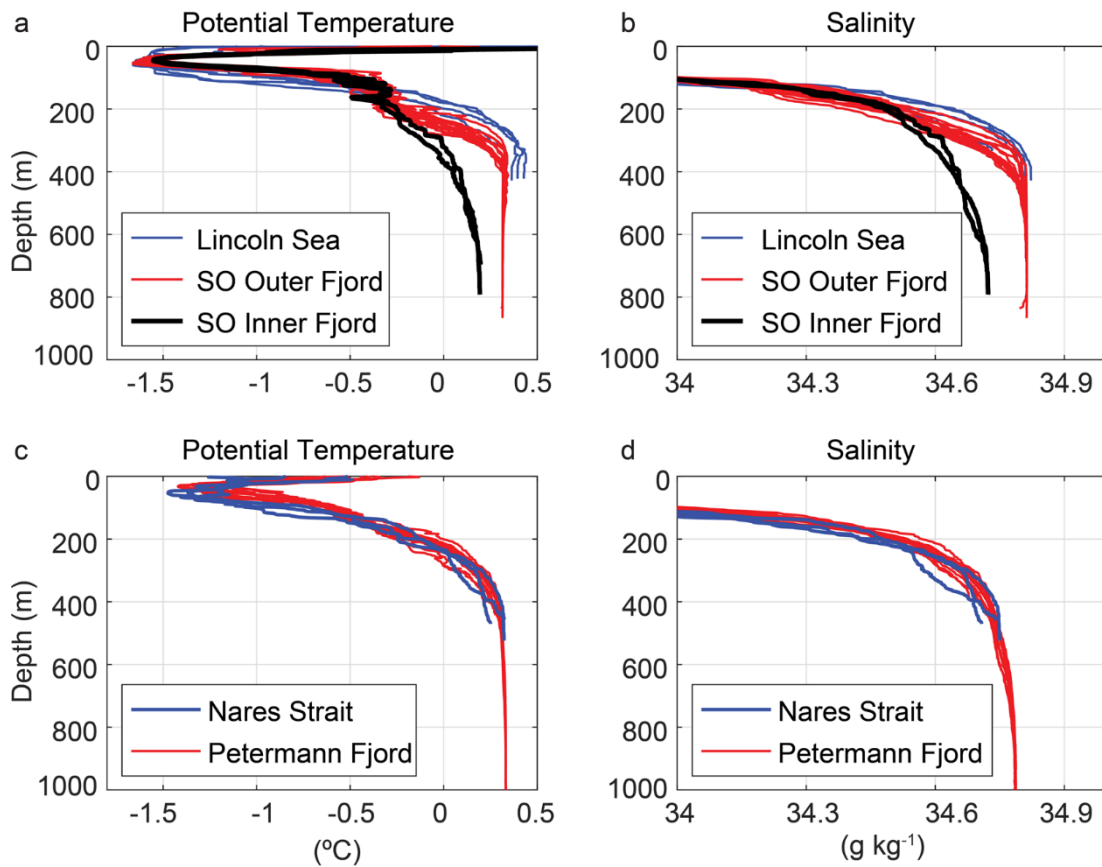
"Indeed, Figures 2d and 4a show that the water below the sill in the inner basin of Sherard Osborn Fjord, which reaches Ryder ice tongue, is both colder and fresher than the AW outside the fjord in the Lincoln Sea."

to

"Supplementary Figure 1d shows that the water below the sill in the inner basin of Sherard Osborn Fjord, which reaches Ryder ice tongue, is colder than the AW outside the fjord in the Lincoln Sea. Further, Figure 4a shows that the densest water, occupying the deep inner basin of Sherard Osborn Fjord, is fresher and less dense than the warmest Lincoln Sea AW, which is typically encountered at depths around 300–400 m (Fig. 2c)"

By comparing specific water masses when referring to Fig. 4a, the point made about the difference in salinity should be clear.

The results of Fig. 2 of Jakobsson et al. (2020) also show that the AW features in Lincoln Sea were broadly similar in 2019 and 2024, and that temporal AW variations are not the cause of the relatively cold and fresh signature of the deep waters in the inner basin of Sherard Osborn Fjord in 2019. We have chosen not to develop this issue here.



I 259-262: Regarding connectivity of AW between Fram Strait and Lincoln Sea, please see my major comments above.

We have addressed the major comments above.

I 261: “who recorded peak ...” is a repetition from I 251-52

This section has been removed in response to the major question

I 267: shouldn't it be “contagious to”?

We have simplified the wording: “a small glacier adjoining the C.H. Ostenfeld Glacier to the northeast...”

I 281: clarify term “bottom-out”

This is now explained and broken up into two sentences in light of Reviewer #2's comment on long sentences: “In addition, there are several icebergs closer to the terminus on the shallower western side of the glacier, taken to be the most recent calving events in this area. Here, there has been so-called ‘bottom-out’ rotation of the newly calved icebergs, i.e., capsizing due to buoyancy adjustment.”

I 265-297: In my view the main point here is to establish that CH Ostenfeld Glacier developed from an ice shelf into a tidewater glacier (main theme of the manuscript). This is convincingly done, and the data are spectacular – including the UAV based data. Yet, how relevant for the main theme is the inference, that possibly on seasonal timescales a small ice tongue may develop? How relevant is the finding, that not all of the glacier is grounded or nearly floating? Scientifically, these are intriguing findings, but maybe some of this should be reserved for a more specific publication. I find the paragraph not well-focussed, but of course I might miss something. I would recommend to sharpen the focus here (shorten the text) or at least to state more clearly, how the findings support the main message.

We thank the reviewer for this thoughtful comment. We agree that the primary purpose of this section is to demonstrate the transition of C.H. Ostenfeld Glacier from a long floating ice tongue to a grounded or near-grounded calving front.

We consider the observations of seasonal and spatially limited flotation to be directly relevant to this main theme, as they demonstrate that the glacier no longer maintains a stable, multi-kilometre floating tongue but instead exhibits a near-grounded terminus that may only transiently approach flotation. To clarify this point, we have revised the paragraph to more explicitly link these observations to the interpretation of a regime shift in terminus dynamics. In particular, we now state that the intermittent and short-lived floating extensions contrast with the former persistent tens-of-kilometres-long ice tongue and underscore the transition to a fundamentally different calving regime. This (underlined) has

been added to sharpen the focus: “Together with an inspection of Landsat imagery dating back to 2002 when the main break-up began (Supplementary Fig. 5), these observations suggest that the terminus of C.H. Ostenfeld glacier may develop a small floating extension during winter, which then disintegrates seasonally via the calving of tabular icebergs upon the break-up of ice mélange in spring/summer. This intermittent and spatially limited flotation contrasts with the former tens-of-kilometres-long, persistent ice tongue and underscores the transition to a fundamentally different terminus regime.”

I 319-350: Most of the conclusion are fine, except for the last one. There is no such thing a persistent high temperatures in the WSC after 2014. The authors should acknowledge this. The should also clearly highlight that CH Ostenfeld Glacier had already started to retreat before 1978, and it is not known when exactly this happened. This makes it difficult to establish a robust link between AW warming in Fram Strait and the disintegration. For the later part of the breakup, after 2001, when using a more robust time series of AW temperature in Fram Strait, this might be possible. Please add this to the conclusions.

Since we removed the analyses of the EN4 data, we removed this last conclusion altogether.

I 390 CH Ostenfeld Glacier had already started before 1978, and it is not known when exactly this happened. This makes it difficult to establish a robust links between AW warming in Fram Strait and the disintegration.

This part has been removed.

I 390-398: The AW temperature time series from EN4 data is not robust. It should not be used.

This part has been removed

Point to point reply in blue font

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

This is my second review of Jakobsson et al., which presents new data surveyed from Victoria Fjord in northern Greenland, and show, in the context of neighbouring glaciers, how the inner and outer sills impact the flow of warm Atlantic water to the terminus of C. H. Ostenfeld glacier.

I appreciate the author's efforts to address my previous comments. I found the paper indeed to be substantially improved, and I appreciate that they have brought the material on C. H. Ostenfeld to the front and centre of the manuscript, both in the text and the Figures. I am satisfied that the paper is suitable for publication now, subject to a few additional line comments I have included below. Note that the line numbers are related to the revised manuscript (not the tracked changes version).

Line comments:

Line 64: need a lead in statement here, e.g. "By comparison, the tongues of Ryder and Petermann Glacier's still extend 10s of km's along their fjords. In 1917 the Ryder ice tongue..." and then remove sentence starting "In contrast to..." on lines 67-68

We have followed this recommendation and inferred a leading statement as well as removed the sentence beginning with "In contrast..".

Line 71: The grounding line sentence still feels out of place here given that you don't mention grounding line movement for the other two glaciers. I suggest removing or putting into better context.

We have followed the advice and removed the sentence.

Line 73: I appreciate the updated research question that does better frame the paper, but I'm not sure this a research question that you can answer in this paper? And is formulated as a general question rather than a testable hypothesis (see later comment for line 123)

We prefer to retain the research question as currently formulated, as it is central to the scope and motivation of both the expedition and the paper. While the question is broad and some aspects remain beyond the scope of this study, we address it by combining oceanographic observations with bathymetric data, which together provide new constraints on Atlantic Water access and its role in submarine melting. We therefore believe that the analyses presented here contribute meaningfully to answering this question within the context of the study. We have followed the later recommendation to modify the hypothesis for a better fit.

Line 80: I'm not sure this paper explores "mechanisms controlling their stability" (e.g.

actually calculating buttressing, or rifting/calving impacts) and rather only the impact of ocean conditions on ice tongue stability. Indeed, that's what the new first line of the abstract alludes to. Perhaps rephrase to that affect.

We appreciate this point. We agree that we do not quantify specific mechanical processes such as buttressing forces or calving dynamics, but rather investigate the environmental controls on ice tongue stability. In this context, we focus on the role of ocean conditions, particularly Atlantic Water access, as a key factor influencing submarine melting and, consequently, ice tongue stability. The statement on Line 80 was meant to be generic and simply points to that understanding the mechanisms are important. However, we have modified it to fit better what we contribute with, and, in fact, it works very well with the used reference by Siegert et al. 2020.

"Understanding the environmental controls on their stability is therefore essential for improved assessments of future sea-level rise¹⁴."

Line 85: "found a transformed fjord" suggests you surveyed it previously, before the ice tongue collapse. I suggest rephrasing.

We see the point and have changed the sentence to: *"We found a transformed Victoria Fjord, changed from a setting of thin and tabular iceberg calving as observed in satellite imagery, to an ice mélange in the inner fjord dominated by remnants of icebergs from numerous calving events."*

Line 91: coincided

Fixed

Line 93: Is Jakobshavn often referred to as an "ice stream". Consider adding the impact of ice tongue loss on inland thinning/ice speeds here as well.

We have added this, with reference to Joughin et al. 2004: "Following the disintegration of the ice tongue, Sermeq Kujalleq exhibited a marked increase in ice flow speed (Joughin et al., 2004)"

Line 103: I don't see the need for this "back-of-the-envelope estimate", why not just present the "more comprehensive estimates"?

We have followed the recommendation and stick to the referencing the papers and having 10-15 years included.

Line 123-124: So here you have the hypothesis you are testing in this paper? But this is not the same as the research question presented on line 73? In fact, Line 73 isn't the paper's research question but rather a more general question.

We have modified the hypothesis for a better fit: *We hypothesize that differences in AW access, controlled by fjord bathymetry, play a key role in the contrasting evolution of northern Greenland's marine-terminating glaciers, with recent warm AW pulses amplifying thinning and retreat where bathymetric conditions allow AW to reach glacier margins.*

Line 156: consider changing “one third” to “first third”

Fixed

Line 173: replace “is slightly more than” with “approximately”

Fixed

Line 181: I assume this should be Fig. 2b?

No it should be 2b where the bathymetry is shown.

Line 303: Is this the correct figures reference? Bed topography is not shown in Supplementary Fig. 4

Thanks for spotting this, it was the wrong figure reference, should be figure 6c

Line 325: There are papers that have shown limited retreat after 2012 that you could cite here.

We have included a citation to Millan et al., 2023, since that paper does show the margin's movement based on satellite imagery.

Line 355-358: I found this sentence a bit too long, consider splitting up or shortening.

Fixed; the sentence is split into two.

Line 372: for the other two glaciers you have said “sill is like this, and tongue is like this” so I suggest doing the same on line 373, “doesn’t have a protective sill, has lost its ice tongue”

Done

Reviewer #3 (Remarks to the Author):

Dear Editor,

I went through the rebuttal letter and the revised manuscript. The authors have accomplished a thorough revision, and my main concern (link to Fram Strait and the EN4 dataset) has been resolved, along with almost all of the remaining items that I put forward. Too bad to learn the ADCP data were not of much use due to low backscattering. I have come across similar situations. Thanks for also providing details on the salinity issue.

I think, now, all main conclusions are well-supported by the analyses provided. I’d like to congratulate the authors on this study, which I am sure will be received by the scientific community with great interest. I strongly support the publication in its current state. The study adds important knowledge on the theme of ocean-glacier interaction in Greenland, by exploring it in the often inaccessible Lincoln Sea area. To my view the manuscript can be published as is.

Cheers,

Torsten Kanzow

No responses required on our behalf and we thank the review for all earlier comments.

The Role of Atlantic water in the break-up of C.H. Ostenfeld Glacier's ice tongue, Northwest Greenland

Martin Jakobsson^{a,b}, Nina Kirchner^{b,c,d}, Johan Nilsson^{b,d}, Christian Stranne^{a,b,f}, Larry Mayer^g,
Jamie Barnett^{a,b}, Felicity A. Holmes^{a,b}, Brian Calder^f, Clemens Deutsch^{h,b}, Agatha M. de Boer^{a,b},
Helen K. Coxall^{a,b}, Karol Faehnrichⁱ, Wei-Li Hong^{a,b,f}, John R. Hopper^{j,k}, Marcelo Ketzer^l, Riko
Noormets^m, Matt O'Regan^a, Neil Rossⁿ, Peter Sigray^h, Elias Strandell Erstorp^{a,b}, Elizabeth
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^aDepartment of Geological Sciences, Stockholm University, Stockholm, Sweden,

martin.jakobsson@geo.su.se; christian.stranne@geo.su.se; jamie.barnett@geo.su.se;

felicity.holmes@geo.su.se; agatha.deboer@geo.su.se; helen.coxall@geo.su.se; [\[li.hong@geo.su.se\]\(mailto:li.hong@geo.su.se\); \[matt.oregan@geo.su.se\]\(mailto:matt.oregan@geo.su.se\); \[elias.erstorp@geo.su.se\]\(mailto:elias.erstorp@geo.su.se\)](mailto:wei-</p></div><div data-bbox=)

^bBolin Centre for Climate Research, Stockholm University, Stockholm, Sweden

^cDepartment of Physical Geography, Stockholm University, Stockholm, Sweden, nina.kirchner@su.se

^dTarfala Research Station, Stockholm Sweden, zhuo.wang@su.se

^eDepartment of Meteorology, Stockholm University, Stockholm, Sweden, johan.nilsson@misu.su.se

^fBaltic Sea Centre, Stockholm University

^gCenter for Coastal and Ocean Mapping, University of New Hampshire, Durham, NH, USA,

larry.mayer@unh.edu; brc@ccom.unh.edu

^hKTH Royal Institute of Technology, Stockholm, Sweden, clemensd@kth.se; sigray@kth.se

ⁱFaculty of Sciences, Engineering and Technology, University of Adelaide, Adelaide, Australia,

karol.faehnrich@adelaide.edu.au

^jDepartment of Geophysics and Sedimentary Basins, Geological Survey of Denmark and Greenland

(GEUS), Denmark, jrh@geus.dk

^kDepartment of Geosciences and Natural Resource Management, University of Copenhagen,

Denmark

^lDepartment of Biology and Environmental Science, Linnaeus University

Kalmar, Sweden, marcelo.ketzer@lnu.se

^mThe University Centre in Svalbard, Svalbard, Norway, riko.noormets@unis.no

ⁿSchool of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, UK,

neil.ross@newcastle.ac.uk

^oDepartment of Marine Sciences, University of Connecticut, Groton, CT, USA, e.weidner@uconn.edu

Abstract (150 words)

The GEOEO *North of Greenland 2024* icebreaker expedition acquired a breadth of data in the unsurveyed Victoria Fjord, north-western Greenland, to assess the causes of the accelerated break-up of the C.H. Ostenfeld ice tongue in 2002, and the environmental changes since. The observations reveal inflow of warm ($>0^{\circ}\text{C}$) Atlantic water reaching the grounded ice margin. We propose that recent Atlantic warm water pulses entering the Arctic Ocean reach north-western Greenland, where they interact with glacier fronts, enhance ice discharge, and amplify the climate-driven retreat of marine-terminating glaciers. The collapse of C.H. Ostenfeld's ice tongue, unlike the slower retreats of the ice tongues of neighbouring Petermann and Ryder glaciers, reflects unimpeded Atlantic water inflow due to the absence of a shielding bathymetric sill, a function of the region's bedrock geology. With Atlantic Water warm pulses projected to intensify by 2026–2028, ocean-driven mass loss of north-west Greenland glaciers are likely.

Introduction

The northern drainage basin of the Greenland Ice Sheet hosts three large outlet glaciers: Petermann, Ryder, and C.H. Ostenfeld, all of which had floating ice tongues exceeding 20 km in length up until 2000, after which C.H. Ostenfeld's tongue began to disintegrate ¹(Fig. 1). These glaciers, which drain into fjords connected to the Nares Strait and Lincoln Sea, together account for approximately 8.5% of the Greenland Ice Sheet's area ². A historical map from 1917 by Danish geologist Lauge Koch indicates that the ice tongues of the Ryder and C.H. Ostenfeld glaciers extended much farther along the fjords than their present-day position (Figs. 1c–e and 2a,b).

Ryder's ice tongue extended 40–45 km beyond its current margin in 1917, although it did not fill the width of Sherard Osborn Fjord at the margin. This extended tongue appears to have broken up prior to 1947 ^{3,4}, and since then the ice tongue has remained relatively stable at roughly its present position ⁵. In 1917, the ice tongue of C.H. Ostenfeld Glacier was mapped >85 km beyond the present grounding line and extended across the entire ~ 18 km-wide Victoria Fjord (Fig. 1c–e). Aerial photographs from 1978 show that the ice-tongue margin had retreated significantly from its 1917 position and began showing signs of fragmentation into icebergs, approximately aligned with Kap Knudsen ³. Between 1978 and 2000, satellite images reveal increasing fragmentation, with the ice tongue successively losing contact with the fjord walls ⁶. By 1992, it was largely broken into icebergs, filling roughly half the fjord's width. Following an advance in 2001/2002 the ice tongue again reached the 1978 position (Fig. 1), but subsequently retreated and had almost completely disintegrated in 2006 ^{7,8} with only a ~ 1.5 km long floating tongue remaining, as observed-satellite-observations. In contrast to C.H. Ostenfeld Glacier, but like Ryder Glacier, the ice tongue of Petermann still exists. Petermann lost approximately 40 % of its

extent during two major calving events in 2010⁹ and 2012¹⁰, but based on Landsat imagery from 2025 it has since advanced around 16 km from the 2012 most withdrawn position (Supplementary Fig. 1). However, the ice tongue has a prominent crevasse located roughly 3 km up-glacier (in the ice-flow direction) from the calving-front position established after the 2012 calving event. Over the last 30 years, the grounding line has retreated by 4–7 km, with most of this retreat occurring between 2017 and 2021¹¹.

Why have these three glaciers with their ice tongues, located within a few hundred kilometres of each other, behaved so differently since 1917? Considering that ice tongues, depending on their configuration, may play an important role in stabilizing outlet glaciers due to their buttressing force and influence on calving¹², the answer to this question is key for proper assessments of future sea-level rise¹³. Here we assess this question in the context of the North Greenland Ice Sheet (NGrIS).

The *GEOEO – North of Greenland 2024 Expedition* (hereafter *GEOEO 2024 Expedition*), with Swedish Icebreaker (IB) *Oden*, became the first ship-based expedition to reach Victoria Fjord. The aftermath of C.H. Ostenfeld's ice-tongue collapse was documented there for the first time, and the first comprehensive dataset of the fjord's environment, including oceanography and seafloor bathymetry, was acquired. We found a transformed Victoria Fjord, changed from a setting of thin and tabular iceberg calving to a chaotic ice mélange in the inner fjord dominated by remnants of icebergs from numerous calving events. Calving at C.H. Ostenfeld now occurs at the grounding line, unlike at Petermann and Ryder where ice tongues remain albeit of different sizes and extents. A similar transformation occurred at Sermeq Kujalleq (a.k.a. Jakobshavn Glacier) in western Greenland after 1997¹⁴. Warmer shelf water had entered the Ilulissat Icefjord, where the glacier drains, leading to melting, thinning, and the eventual break-up of the ice-tongue. This loss of the ice tongue caused enhanced calving of the ice stream and triggered the prolific production of large icebergs, which in turn substantially affected the fjord circulation¹⁵.

The impact of relatively warm ($>0^{\circ}\text{C}$) Atlantic Water (AW) has also been observed in northern Greenland, where it has potentially contributed to two major calving events of Petermann Glacier in Petermann Fjord, in 2010 and 2012¹⁶. The AW flows into the central Arctic Ocean via two major branches, through the Fram Strait and across the Barents Sea¹⁷. Only after circulating counterclockwise around the Arctic Ocean Basin is the AW able to spill over the Lincoln Sea shelf and make its way into the north-western Greenland fjords (Fig. 1). This journey takes about 12 years from the Fram Strait, using an average flow speed of 0.02 ms^{-1} ^{18,19}. While the core of Atlantic water progressively sinks and cools along the circulation pathway¹⁷, it maintains $>0^{\circ}\text{C}$ when reaching North Greenland.

The *Ryder 2019 Expedition* with IB *Oden* found that AW also enters Sherard Osborn Fjord, where Ryder Glacier drains. However, here a shallow bathymetric sill significantly reduces further inflow, thereby shielding the glacier and making it less susceptible to the inflowing warmer AW²⁰. The *GEOEO*

2024 Expedition investigated whether AW also reaches Victoria Fjord, testing whether protective bathymetric sills are present there, shielding C.H. Ostenfeld Glacier from AW, as they do Ryder Glacier in Sherard Osborn Fjord. Here we present new data from the previously unsurveyed Victoria Fjord and compare physical settings and oceanographic conditions among the three glaciers. We hypothesize that, while AW inflow into the Arctic Ocean is a long-standing feature, recent warmer pulses have amplified the thinning and retreat of northern Greenland's marine-terminating glaciers in areas where geological conditions allow AW to reach the glacier margins. The ice dynamics of the outlet glaciers of the NGrIS vary due to geological settings, fjord geometry, presence of bathymetric sills⁵, and grounding line shape^{2,6}. In particular, the abrupt collapse of C.H. Ostenfeld's ice tongue, unlike the more gradual retreat of Petermann's and the relatively stable position of Ryder's, suggests that fjord and glacier conditions modulate responses to oceanic forcing. Testing the hypothesis that recent pulses of AW are controlling ice dynamics in North Greenland requires oceanographic data (such as fjord-wide temperature profiles), along with detailed bathymetry, and subglacial topography. These datasets, together with radio-echo sounding (RES) of the ice-margin area, also permit determination of whether the glacier front is primarily grounded or floating.

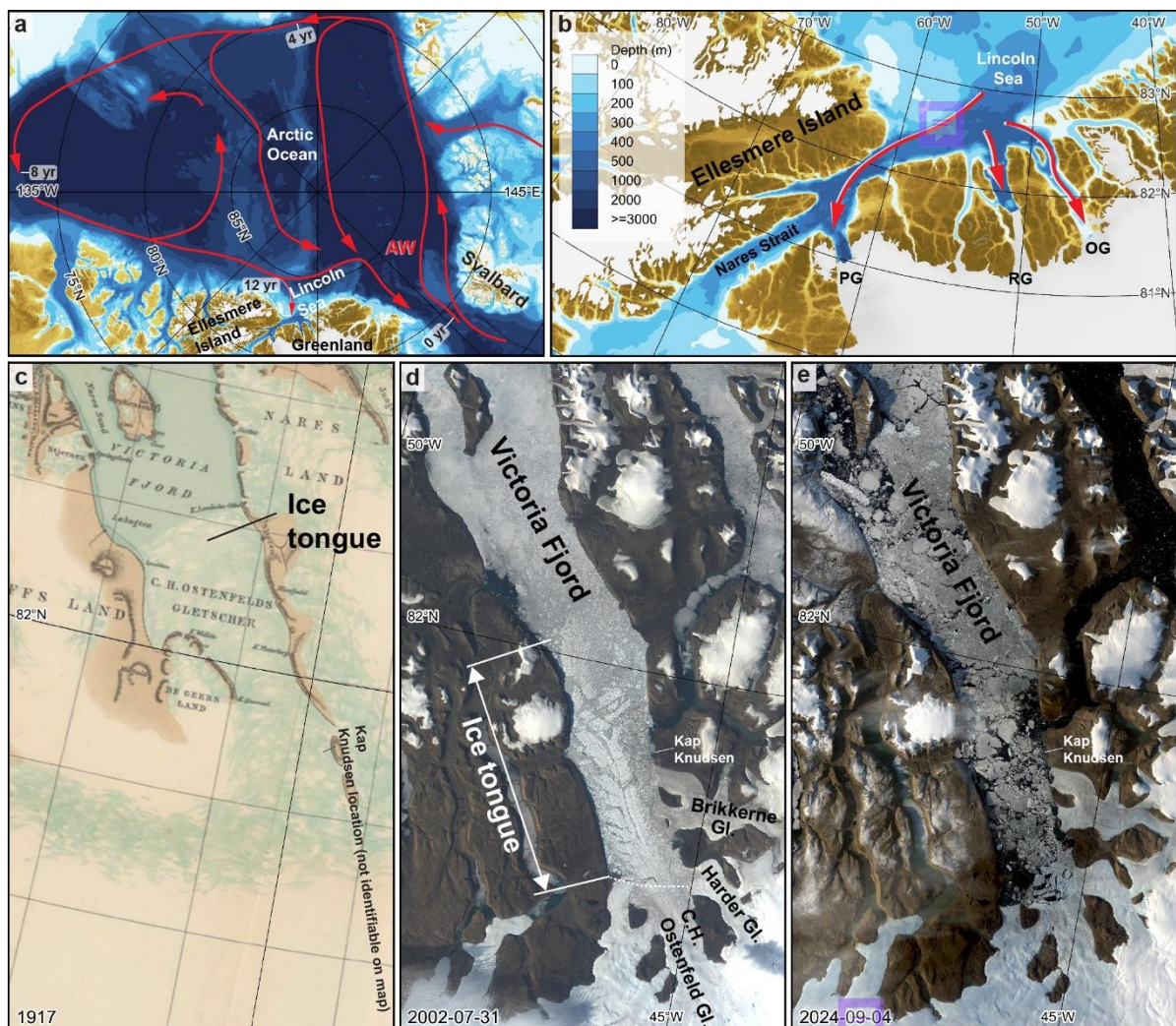


Figure 1. Maps showing the regions of focus for this study. **(a)** North Greenland Ice Sheet (NGrIS) and general flow of Atlantic Water (AW), which enters the Arctic Ocean through Fram Strait and the Barents Sea, circulating counter clockwise along the Arctic Ocean continental slope before reaching North Greenland. The schematic AW flow (core depth of about 200–400 m) is illustrated by red arrows. Rough estimates of the transit time in years for the AW is shown using an average flow of 0.02 ms^{-1} (see text). **(b)** Detailed map of the Lincoln Sea and locations of the three marine-terminating glaciers: Petermann (PG), Ryder (RG), and C.H. Ostenfeld (OG). **(c)** Historical map from 1917 by Danish geologist Lauge Koch showing the ice-tongue extent of C.H. Ostenfeld Glacier. **(d–e)** Landsat satellite images showing the extent of the C.H. Ostenfeld ice tongue before and after its complete break-up.

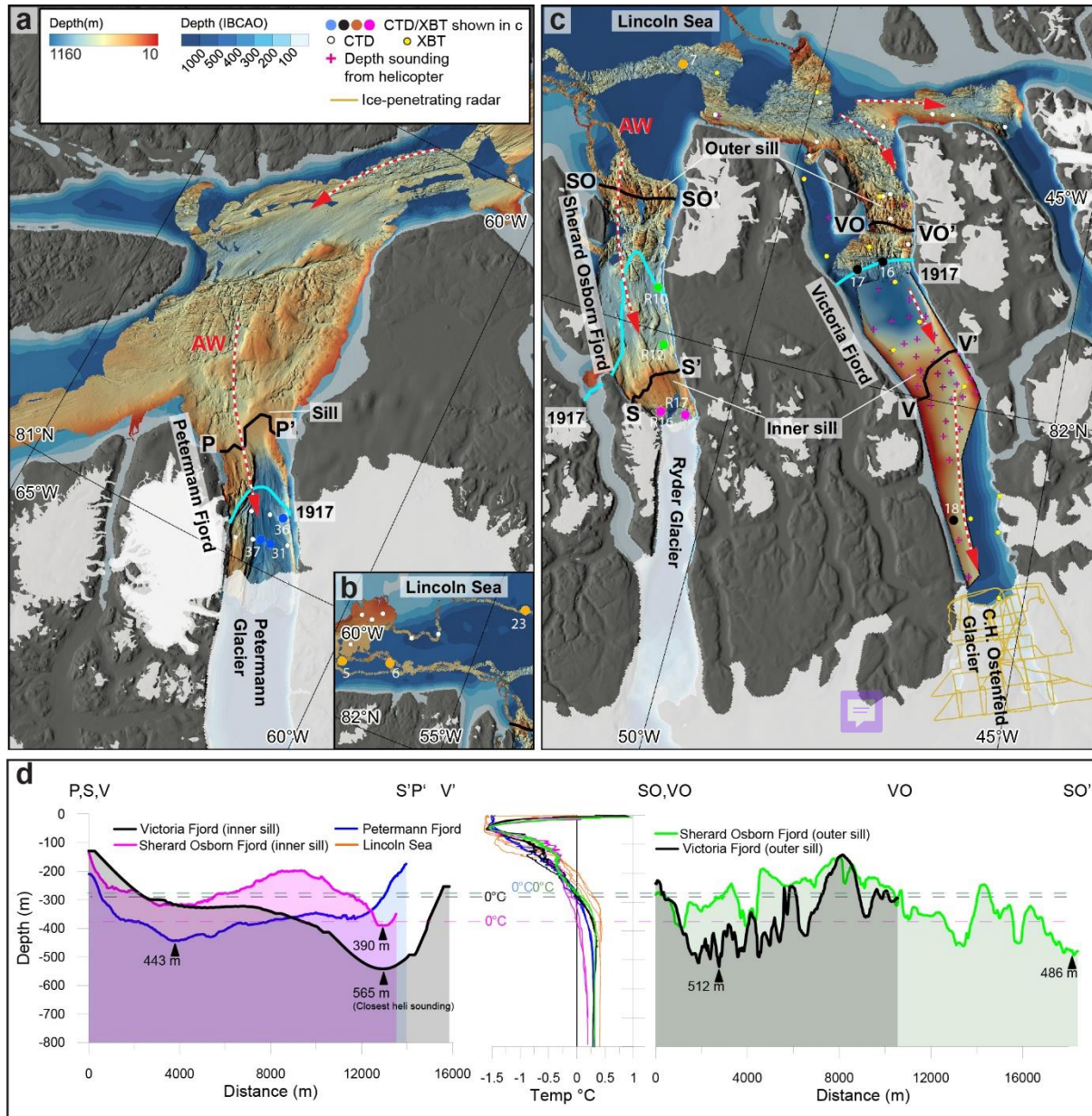


Figure 2. Detailed bathymetric maps and data from Petermann, Sherard Osborn and Victoria fjords. **(a–c)** Maps showing seafloor bathymetry from multibeam mapping and spot soundings (pink crosses). The background bathymetry, shown in a blue colour scheme, is based on the International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 5.0²¹, updated in this study with the new depth data acquired during the GEOEO 2024 Expedition. Locations of temperature profiles acquired

with CTD and XBT instruments are marked with filled circles. The 1917 ice-tongue margins mapped by Lauge Koch are shown in turquoise. Schematic subsurface AW flow inferred from temperature profiles is indicated by red arrows. **(d)** Color-coded bathymetric profiles across mapped sills and temperature profiles. The bathymetric profile locations are shown in **(a-c)** with black lines. Black arrows mark the approximate deepest passages across the sills, along with their depths. Temperature profiles are color-coded according to their locations on the maps and marked with white numbers denoting the station (R mark stations from Ryder 2019 expedition). The approximate vertical position of the 0 °C isotherm is inferred from the temperature data using the same colour coding as for the temperature profiles.

Results and discussion

Bathymetry and geology

The outer, approximately one-third of the 116 km-long Victoria Fjord was bathymetrically mapped using multibeam echo sounder; a high concentration of icebergs prevented the icebreaker from progressing farther into the fjord (Supplementary Fig. 2). Information about the seafloor in the unmapped inner part was therefore acquired by obtaining spot depth soundings using a single-beam echosounder deployed from a helicopter (Fig. 2b, Supplementary Fig. 3). The multibeam bathymetry together with all spot soundings have been used to update the most recent version the International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 5.0 ²¹ Digital Terrain Model (DTM), which in turn uses BedMachine Version 5 for the under ice topography and inner fjord bathymetry ²²(see Methods; Supplementary Fig. 4).

At the mouth of Victoria Fjord, a prominent bathymetric outer sill was identified. It resembles in its shape and form the outer sill of nearby Sherard Osborn Fjord and aligns with the same bedrock comprised of steeply dipping beds of deformed Silurian deep water turbidites and older shelf to basinal deposits of the Franklinian Basin ²³ (Figs. 2 and 3). The sills are situated on the main fold and thrust belt of the Devonian–Carboniferous Ellesmerian orogen exposed on Greenland ²⁴. The outer sill in Victoria Fjord is slightly deeper, with a threshold depth of ~512 m, compared to ~486 m in Sherard Osborn Fjord (Fig. 2). Further into the fjord, inside this outer sill, the seafloor deepens to a maximum of ~1100 m. The spot soundings indicate the presence of an inner sill in Victoria Fjord corresponding to a belt of resistant carbonate reefs belonging to the Silurian Washington Land Group ^{23,25} (Figs 2 and 3). The same bedrock forms the base of a shallow inner sill that nearly continuously extends across Sherard Osborn Fjord and greatly restricts the inflow of AW ²⁰. Sherard Osborn Fjord only has an approximately 1 km wide channel at its eastern side of the inner sill where the water depth reaches a maximum of ~390 m. In Victoria Fjord, however, the inner sill does not span the entire width of the fjord. A distinct, deep channel begins around the 400 m isobath and is more than 7 km wide (Fig. 2). Based on our spot soundings, the deepest point of this passage has a water depth of about 565 m (Supplementary Fig. 4). Inland of the sill, the fjord deepens again. The bathymetry of the innermost

section, about 44 km from the ice margin, is constrained by only four spot soundings (Fig. 1c, 628, 376, 622, and 514 m, N–S). Three additional measurements indicated depths greater than 450 m, but a problem in the echosounder configuration limited the recordings below this depth threshold during the deployment.

The Silurian Washington Land Group extends westward beyond Sherard Osborn Fjord and aligns with the prominent sill at the entrance of Peterman Fjord (Fig. 3). This bathymetric shoal forming the sill has a maximum water depth of about 443 m²⁶ and is generally deeper than the inner sill in Sherard Osborn Fjord. The bathymetric profile across the sill at the mouth of Petermann Fjord more closely resembles that of the inner sill in Victoria Fjord, although the deepest passage is located to the west rather than the east.

Merging the bathymetry with available geological maps, it becomes strikingly clear that the geological formations of north-western Greenland align with the mapped bathymetric sills in Victoria, Sherard Osborn, and Petermann fjords (Fig. 3). The dynamics of the outlet glaciers in Sherard Osborn and Petermann fjords, both at present and over longer timescales, have been shown in previous studies to be strongly influenced by these sills^{20,27,28}. This suggests that regional geology exerts a fundamental control on the fjord bathymetries, and thereby on glacier behaviour. In the following, we analyse whether the oceanographic data collected from Victoria Fjord reveal a similar sill influence on the present conditions of C.H. Ostenfeld Glacier.

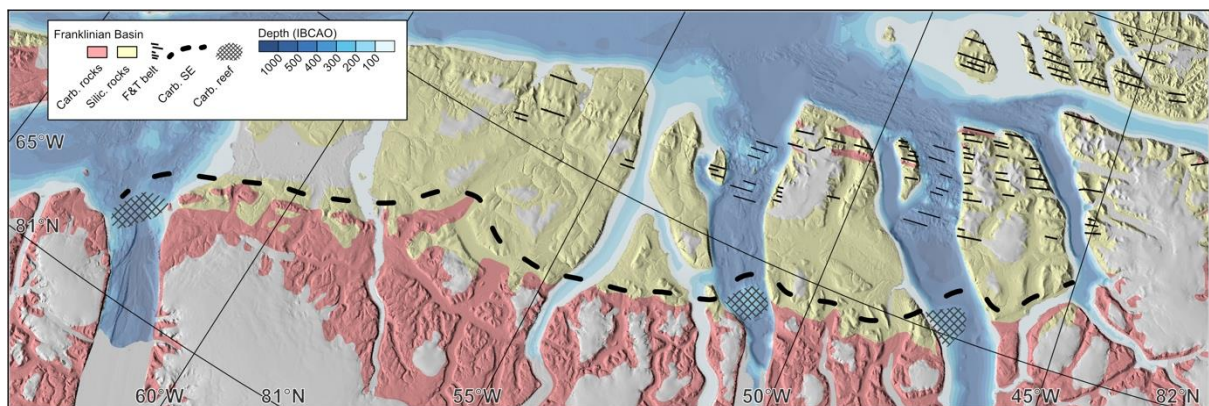


Figure 3. Geological formations on north-western Greenland aligning with mapped bathymetric sills in Victoria, Sherard Osborn and Petermann fjords. Abbreviations: carb. - carbonate; silic. - siliciclastic, F&T - fold and thrust; SE - shelf edge. Geological information is from Hopper and Ineson²⁹

Oceanography

During the *GEOE 24 Expedition*, temperature and salinity profiles were collected from IB *Oden* in the Lincoln Sea, and throughout Victoria and Petermann fjords using a CTD (conductivity, temperature, depth) probe (Fig. 2). In the southern two-thirds of Victoria Fjord, inaccessible to IB *Oden*, temperature

data were acquired using XBTs (expendable bathythermographs) launched from a helicopter. To compare the ocean temperature structures in Victoria and Sherard Osborn fjords, we use the oceanographic data from the *Ryder 2019 Expedition*^{20,30}, while the comparison with Petermann Fjord is based on the data collected during the *GEOEO 2024 Expedition*. Subsurface water masses with temperatures above 0°C are inferred to be AW, as there is no other known source of warm water in the region.

In 2024, waters in the Lincoln Sea and the outer part of Victoria Fjord reached temperatures above 0°C at depths deeper than about 200–275 m (Fig. 2d). Water with a temperature above 0°C was observed at slightly greater depths of ~290 m in the inner fjord of Victoria Fjord, i.e., landward of the inner sill, indicating the full intrusion of AW all the way to the ice margin of C.H. Ostenfeld Glacier (Fig. 2d). This is consistent with the bathymetric data from Victoria Fjord, which, as previously described, show a >400 m deep and ~7 km wide passage in the inner sill. In contrast, Sherard Osborn Fjord has a nearly continuous inner sill spanning the fjord, and temperatures there first reach 0 °C at much deeper depths of ~350–375 m landward of this sill.

Figure 4 shows the temperature–salinity relationship for AW in the Lincoln Sea, and Victoria and Petermann fjords for selected stations taken during the *GEOEO 2024 Expedition*; observations taken near the front of Ryder Glacier in 2019 are also shown. The maximum AW temperature in Lincoln Sea, observed in 2024, was slightly above 0.4 °C, and AW temperatures reaching 0.35 °C were encountered in the Victoria Fjord CTD and XBT measurements. In Petermann Fjord, the temperatures around the sill level (~440 m) were colder than at similar depths in the Lincoln Sea and Victoria Fjord (Fig. 2d). However, the temperature increases with depth in Petermann Fjord reaching ~0.3 °C at around 1000 m, indicating that inflows of warmer AW from the Lincoln Sea occasionally spill over the sill. Similarly, the cooler temperatures in the deep Victoria Fjord presumably reflect past inflow events, which carried colder but more saline AW into the deep fjord basin.

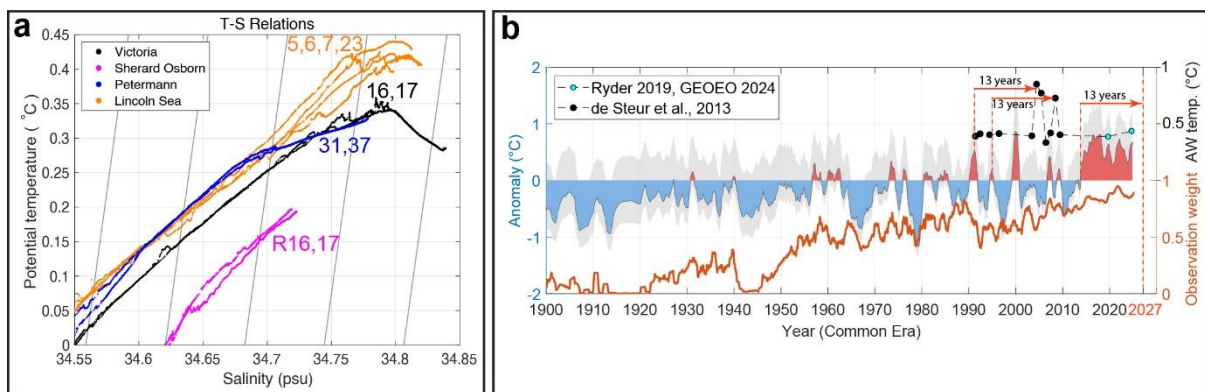


Figure 4. Temperature–salinity relationship for Atlantic Water (AW) in the Lincoln Sea, and Victoria, Sherard Osborn and Petermann fjords, and long-term trends in AW temperature anomalies. (a) The temperature-salinity data are based on CTD stations shown in Figure 2. Station numbers are show next

to the profiles in corresponding colours. The inner part of Victoria Fjord, beyond the reach of IB Oden and only sampled by XBT, which lacks salinity data, is not included in the comparison. **(b)** Monthly means of potential temperature anomaly in the 200–500 m depth interval from 1900 to present, based on the EN4 dataset gridded at 1° resolution within 77–80°N and 0–10°E (see Methods).

The maximum temperature in the inner Sherard Osborn Fjord, near the front of Ryder Glacier ice tongue, was notably colder than the AW temperature maximum outside the inner sill in the main fjord in 2019. The reason for this is the sill geometry in Sherard Osborn Fjord: as the AW flows towards the glacier over the relatively shallow inner sill, it mixes with colder and fresher outflowing water that has been modified by glacier–ocean interactions^{20,31}. Indeed, Figures 2d and 4a show that the water below the sill in the inner basin of Sherard Osborn Fjord, which reaches Ryder ice tongue, is both colder and fresher than the AW outside the fjord in the Lincoln Sea. Importantly, the flow and its associated mixing over the inner sill provides a stabilising dynamical feedback to ocean warming: AW temperature changes in the Lincoln Sea yield a muted temperature response at the grounding line of Ryder Glacier^{20,31}.

The observed AW features in Victoria Fjord, suggest that the C. H. Ostenfeld Glacier is more susceptible to changes in AW temperature than Ryder glacier. The C.H. Ostenfeld Glacier is exposed to AW from the Lincoln Sea that is apparently only slightly cooled along its flow into Victoria Fjord while Ryder Glacier is, as mentioned, protected by the prominent inner bathymetric sill.

The Lincoln Sea CTD stations taken during the *Ryder 2019* and *GEOEO 2024 Expeditions* have AW temperature maxima in the range 0.35–0.44 °C. Notably, AW temperature maxima have been reported in the range 0.35–0.8 °C from ice-tethered measurements in the Northern Lincoln Sea, near or on the continental slope³². These measurements cover the period 1991–2009, with a data gap between 1997 and 2002, and reveal temporal as well as spatial variations; particularly high AW temperatures occur in 2004, 2005 and 2008. Corresponding measurements of AW in the Southern Lincoln Sea, closer to Victoria Fjord, are lacking. However, it cannot be ruled out that anomalously warm AW (~0.8 °C) has occasionally reached Victoria Fjord in the past, and may do so again in the future.

Data on AW temperature extracted from west of Svalbard (77–80°N/0–10°E), extending back to 1900 (see Methods), reveal a general warming trend (Fig. 4b). Warmer pulses began to emerge after 1930, intensified from 1991, and developed into a more coherent, prolonged warm pulse after around 2014. The core of the AW in the central Arctic Ocean lies at a depth of about 200–400 meters¹⁷. As previously mentioned, a rough estimation yields that the AW pulses will reach the Lincoln Sea at around 12 years after entering the Arctic Ocean through the Fram Strait. This timing aligns well with observations made in the north western Lincoln Sea by de Steur et al³², who recorded peaks of AW temperature in 2004, 2005 and 2008, potentially linked to a series of warm AW pulses that entered the Arctic Ocean some 10–15 years earlier (Fig. 4b).

Ice margin geometry from radio-echo sounding and drone measurements

Profiles from radio echo-sounding (RES) at the margin of C. H. Ostenfeld Glacier indicate a non-floating calving cliff during the survey time, 21-26 August 2024 (Fig. 5), except for along a ~4 km stretch in the east and at the northernmost part of Harder Glacier (a small glacier to contiguous but to the northeast of C.H. Ostenfeld Glacier; Fig. 1d), where short floating extensions of about 0.4–0.9 km are present (Fig. 5; Supplementary Fig. 5b). In C.H. Ostenfeld's central sector, the margin is grounded at a depth of ~360 m and it rises to ~35 m above sea level (Fig. 5). Grounding depths vary along the margin and are generally shallower at C.H. Ostenfeld's western section. The bed elevation derived from the RES profiles shows a poor match in places with the BedMachine Version 5 under-ice topography, particularly in both the westernmost and easternmost sectors (Supplementary Fig. 4).

The height of the calving cliff along the central section of C.H. Ostenfeld's eastern margin was determined in detail from topographic mapping by an uncrewed aerial vehicle (UAV) (Fig. 5). The UAV imagery additionally allows for calving dynamics at C.H. Ostenfeld to be deduced from the characteristics of recently calved icebergs. In the vicinity of the terminus, there are many large, tabular icebergs (up to ~3×0.7 km in size), the presence of which suggests a calving style associated with a floating terminus³³. In addition, there are several icebergs closer to the terminus on the shallower western side of the glacier, taken to be the most recent calving events in this area, where there has been 'bottom-out' rotation of the icebergs. Bottom-out rotation has been previously observed in Greenland and described as slab capsize or buoyant flexure calving, thought to be indicative of glaciers nearing/at flotation. These icebergs are up to 200 m long, suggesting they represent the full thickness of the glacier in this region. Together with an inspection of Landsat imagery dating back to 2002 when the main break-up began (Supplementary Fig. 5), these observations suggest that the terminus of C.H. Ostenfeld glacier may develop a small floating extension during winter, which then disintegrates seasonally via the calving of tabular icebergs upon the break-up of ice mélange in spring/summer. After the removal of the small floating section, there is a shift in calving style to buoyant flexure calving, indicating a grounded terminus near flotation. This kind of seasonal shift is not unprecedented in Greenland. For example this was suggested following UAV surveys at Store Glacier³⁴. Furthermore, the Landsat imagery shows that by 2012 the margin was for the most part less than 1 km away from that of 2024, apart from along the western side, showing how there has been little net movement of the terminus in over a decade.

Taken together, the radargrams and UAV surveys indicate that Victoria Fjord has undergone a long-term regime shift from hosting an outlet glacier ending with a tens of kilometres long floating ice tongue to a glacier with a near-grounded calving cliff, a transition comparable to the shift observed at Ilulissat when Sermeq Kujalleq evolved from ice-tongue calving to ice-cliff calving¹⁵.

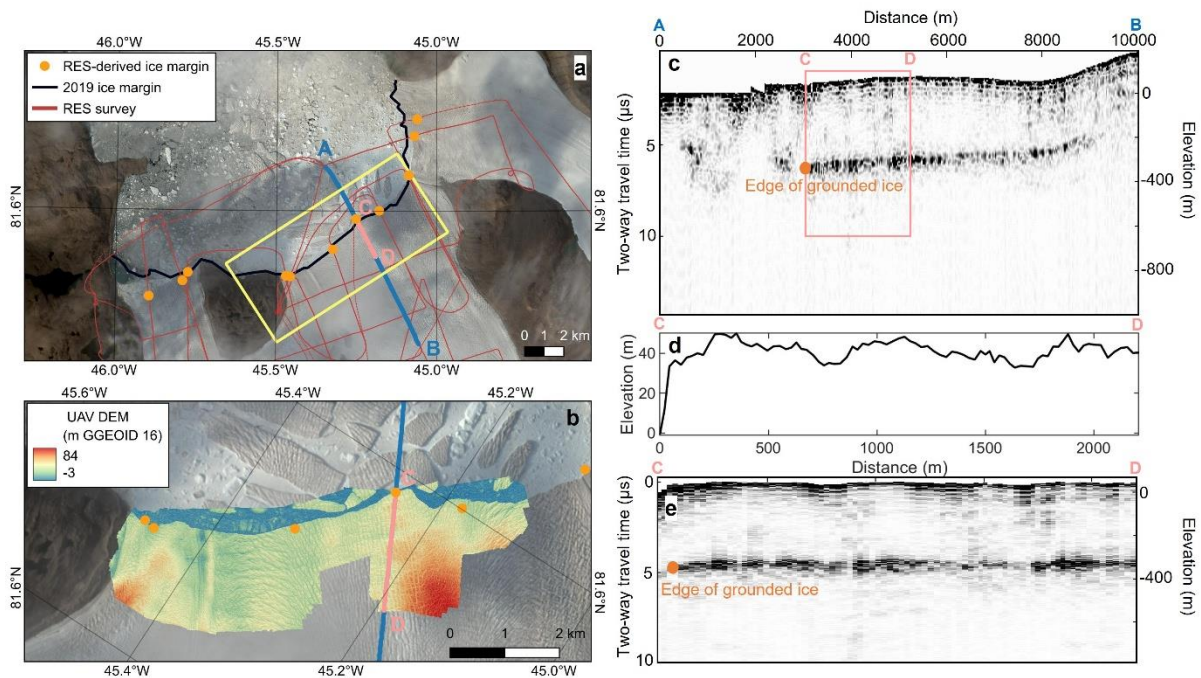


Figure 5. Radio-echo sounding (RES) and uncrewed aerial vehicle (UAV) observations at C.H. Ostenfeld Glacier; constraining the ice margin during the GEOEO 2024 expedition (August 2024). **(a)** RES data acquisition (red lines) at C.H. Ostenfeld glacier 21st-26th August 2024. Backdrop is pansharpened Landsat 9 true colour satellite imagery acquired 23rd August 2024. Black line is 2019 ice margin position ⁶. Orange dots are RES-derived ice margin (21st-26th Aug 2024) based on termination of bright basal reflection in the radargrams. The yellow frame shows the location of Fig. 5b. Blue and pink lines represent the locations of radargrams shown in Fig. 5c and Fig. 5e, respectively. **(b)** UAV-derived Digital Elevation Model of the ice surface on 27th August, 2024. Backdrop is pansharpened Landsat 9 true colour acquired on 23rd August 2024. UAV DEM is relative to GGEOD16 ³⁵. Map is rotated 33° clockwise relative to Fig. 5a. **(c)** Arctic DEM corrected RES data along the trunk of C.H. Ostenfeld (from A to B). Elevation correction performed using 2 m Arctic DEM mosaic (v4.1), so ice surface profile is not fully representative of the ice topography at time of RES data acquisition. **(d)** Ice surface elevation profile across UAV derived DEM with the resolution of 49 cm (relative to GGEOD16). Extent corresponds to Fig. 5e. **(e)** UAV DEM corrected RES data along the first ~2 km of the C.H. Ostenfeld trunk. Extent corresponds to Fig. 5d. Note correspondence between end of bright bed reflection and break in ice surface slope at time of survey.

Conclusion

Analyses of data acquired from Petermann Fjord, Nares Strait, Lincoln Sea, and the previously unsurveyed Victoria Fjord during the GEOEO 2024 Expedition, together with observations from Sherard Osborn Fjord made during the Ryder 2019 Expedition, allow us to address the hypothesis that recent pulses of warmer Atlantic Water have amplified the thinning and retreat of northern Greenland's marine-terminating glaciers (Petermann, Ryder, and C.H. Ostenfeld) in areas where geological conditions allow AW to reach the glacier margins.

- Victoria Fjord, where the C.H. Ostenfeld Glacier drains, has undergone a fundamental regime shift since 1917. The glacier has transitioned from possessing a tens-of-kilometres-long floating ice tongue to forming a grounded calving cliff that is now close to floatation. This change represents a shift in glacier dynamics: large tabular icebergs calve in early summer following the melting of the buttressing winter ice mélange, after which the glacier transitions to calving via buoyant flexure and cliff failure at a grounded front. This has likely altered fjord circulation and may further impact the marine ecosystem.
- Bathymetric mapping shows that, unlike Sherard Osborn Fjord, Victoria Fjord lacks a shallow protective inner sill, allowing Atlantic Water (AW) to penetrate to the glacier grounding line with only minor modification. This geometry exposes C.H. Ostenfeld Glacier directly to warming AW, making it more vulnerable than neighbouring outlet glaciers.
- The neighbouring Petermann and Ryder glaciers illustrate how sill depth and fjord geometry modulate glacier response to similar regional ocean forcing. Petermann, with a deeper and less protective sill, retains a weakened but persisting ice tongue; Ryder is effectively shielded at its present location by its inner sill; whereas C.H. Ostenfeld has already lost its ice tongue entirely and changed calving regime.
- Regional geology exerts a strong influence on these glacier systems, as the position and geometry of sills in all three fjords are linked to underlying bedrock structure.
- Warm AW water pulses that entered the Arctic through the Fram Strait from 2013 are expected to reach North Greenland outlet glaciers beginning 2026-2028, which will lead to varying degrees of melting depending on fjord configuration. With C.H. Ostenfeld having already lost its floating tongue, the question remains how long Ryder and Petermann glaciers can sustain their current configurations before undergoing comparable transitions. These changes carry direct implications for enhanced ice discharge from northern Greenland and its contribution to future sea-level rise.

Methods

The complete data acquisition during the *GEOEO – North of Greenland 2024 Expedition*, henceforth referred to as the *GEOEO 2024 Expedition*, is described in the cruise report³⁶. Here follows a summary of the methodologies applied to collect the data presented in this paper.

Bathymetric mapping

Bathymetric mapping with Swedish IB *Oden* was conducted during the *GEOEO 2024 Expedition* using the same methodology as during the *Ryder 2019 Expedition*, previously described by Jakobsson et al.³⁷. This involved mapping with the installed Kongsberg EM122 (12 kHz, 1° × 1°) multibeam echosounder, which receives positions and attitude information from a Kongsberg/Seatex Seapath 320 navigation system with a MRU5 motion sensor. To calibrate the multibeam echosounder, sound speed profiles derived from both XBTs (Expendable BathyThermographs) and CTDs (Conductivity,

Temperature, Depth) were used (see below). The depth data are referenced to instantaneous sea level. All bathymetric data were processed using QPS Qimera software, version 2.6.2. Grids with cell sizes ranging from 15×15 m in the shallowest areas to 30×30 m in the deepest were produced and used to create maps with the Open Source QGIS software version 3.40.8.

Where the icebergs and ice mélange in Victoria Fjord prevented IB *Oden* from entering the fjord, 46 attempted spot soundings were successfully acquired by dipping a Kongsberg EK80 WBAT 38 kHz echosounder from a helicopter. The instrument was mounted on an aluminium frame and automatically triggered at 8 m below the water surface by a pressure switch, then deactivated upon retrieval at 4 m. A buoy was attached 10 m above the frame to guide the helicopter pilot during dipping at each spot sounding location. All spot soundings were calibrated using nearby mean sound speed values and imported into QGIS, where they were gridded using a spline interpolation function.

The IBCAO Version 5.0 bathymetric grid was updated by removing the fjord bathymetry derived from BedMachine Version 5 in areas where new depth data were acquired during the GEOEO 2024 Expedition. The new depth data were then incorporated into the IBCAO 5.0 gridding algorithm²¹, which interpolates a continuous bathymetric surface to fill the areas previously cropped from BedMachine. In addition, depth contours were manually inferred to support the gridding, following the IBCAO procedure used in regions where data are too sparse for unconstrained interpolation, which can otherwise cause the continuous spline in tension gridding algorithm to over- or undershoot. This approach necessarily involves some degree of manual interpretation of the bathymetry.

Oceanography

A Seabird 911+ CTD was used from IB *Oden* to acquire temperature profiles at oceanographic stations. During the downcast, the CTD was lowered at a speed of approximately 0.5 m s⁻¹ and stopped about ten meters above the seafloor, as measured by a pinger installed on the rosette frame holding the CTD. In areas of Victoria Fjord that IB *Oden* could not reach, temperature data were acquired using XBTs launched from a helicopter. Only a few XBTs failed to provide reliable data; those selected for Figure 2b in the main article were found to represent the general temperature structure in their respective areas of Victoria Fjord.

Analysis of Atlantic water anomalies

The temperature anomaly of Atlantic Water (AW) shown in Figure 2c of the main article is based on EN4³⁸, a global, quality-controlled dataset of observed potential temperature and salinity profiles widely used in climate studies^{39,40}. It combines data from all types of profiling instruments and platforms. The dataset is gridded at 1° horizontal resolution and provides monthly means from 1900 to the present. The AW anomalies shown in Figure 2c are based on data from a box west of Svalbard, bounded by 77–80° N and 0–10° E, and calculated as the mean potential temperature in the 200–500 m depth interval.

Only data with salinity > 34.9 were included to capture the core of the Atlantic layer circulating within the Arctic Ocean while excluding surface waters influenced by local atmospheric forcing.

In the absence of observations, EN4 defaults to a 1971–2000 climatology³⁸. The observation weight variable (ranging from 0 to 1) indicates data coverage, where 0 means climatology is used and values close to 1 indicate strong observational influence. To estimate the uncertainty of monthly box-averaged temperatures, we conservatively assumed fully dependent errors and calculated the standard error as the arithmetic mean of individual grid cell uncertainties provided in the EN4 dataset. This yields an upper bound on the uncertainty in the monthly mean.

Radio-echo sounding

During the *GEOEO 2024 Expedition*, a radio-echo sounding (RES) system, a.k.a. ice-penetrating radar, from Blue System Integration Ltd (v3.) was used to map the ice thickness of C.H. Ostenfeld Glacier in its wider terminus region. The radar was mounted beneath one of the expedition helicopters in a cross-antenna configuration. It operated with wavelength of 16.8 m in ice and a sampling rate of 125 MHz⁴¹. Data acquisition missions were planned along a regular grid, however, occasionally, conditions met during the surveys (mainly wind and visibility) required some deviations. The surveys were flown at an altitude of about 30–50 m above the ice surface, at speeds ranging between 22 and 30 kn. The survey trajectory was tracked by a GPS receiver integrated in the radar system. Raw data was post-processed using REFLEXW (<https://www.sandmeier-geo.de/reflexw.html>) including static correction, elevation correction, dewow, bandpass filter, gain function and 2-D filter. The surface and bed of the glacier were manually identified in the radar profiles, and the ice-thickness was derived assuming a radio-wave velocity of 0.168 m ns^{-1} in ice.

UAV (drone mapping)

Drone mapping of the terminus of C.H. Ostenfeld Glacier was done using two DJI Mavic 3E drones with GPS-RTK modules connected to a DJI RTK-2 mobile station. The drones were flown using a pre-programmed flight plan, at a height of 450 m above the glacier surface and collected images with a side overlap of 70% and a front overlap of 80%. The survey was conducted on August 27th 2024 and resulted in 585 photographs. These images from the survey were then post processed using Metashape Pro to create a final DEM (Digital Elevation Model) with a resolution of 49 cm and vertical heights relative to the Greenland geoid GGEOID16.

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Author contribution statements

MJ, NK, JN, CS, LM conceived the idea of the paper; MJ made the first draft and led the writing. JN and CN analysed the oceanographic data while MJ, LM, BC, RN, and EW compiled and analysed the multibeam bathymetry. CD, PS, CS, ES, NR and MJ retrieved XBTs and spot soundings from helicopter. JB and FH compiled and analysed the drone data. NK, NR and ZW compiled and analysed the radio-echo sounding data. JRH and KF have provided specifics on the bedrock geology. All authors have commented on the paper. Group authors listed in supplementary information have read the paper, acknowledged their participation, made comments at various degrees, and participated in different aspects on data collections during the expedition.

464

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