Reviewer 2:

Manuscript Summary

This manuscript presents the results of ISSM simulations of Ryder Glacier, North Greenland, through the Holocene, constrained by preexisting terrestrial reconstructions and marine sediment records. They aim to better understand the drivers of Holocene ice sheet retreat and advance. Their results show that retreat following the Younger Dryas was SMB driven, with ice-ocean interactions becoming more important during the mid-Holocene. They also demonstrate that the Neoglacial advance of Ryder Glacier requires ice tongue regrowth, which required both cooling ocean temperatures and air temperatures.

The manuscript is well-written and structured, effectively addressing the paper's objectives. It is very well illustrated, which helps me (and any reader) to understand what is being presented. The interpretations are clear and well supported by the results presented.

I don't have many major criticisms or concerns with the paper, but I think some aspects of the writing should be improved. There are numerous typos and incorrect word choices which limit the understanding of the content at times. I've included some below, but there are more.

Thank you for taking the time to read and comment on our manuscript. We have responded to each of the points individually below in blue.

Minor comments:

The decision behind the choice of model is not very clearly explained. Given the dependence of the paper on this, and as a non-modelling expert, I feel it would be beneficial to explain the choices for this glaciological and topographic situation.

We thank the reviewer for highlighting this section of the manuscript and note that Reviewer #1 had a similar point regarding model set up. To address this, we have re-written our initial paragraph in our methods section that describes why we chose to use the Blatter-Pattyn Higer-Order (HO) approximation for our study and not the Full-Stokes (FS) equations.

Re-written model set up:

The finite-element thermomechanical ice-sheet model ISSM is employed to simulate the Holocene history of Ryder Glacier (Larour et al., 2012) together with a Higher-Order (HO) approximation (Blatter, 1995; Pattyn, 2003) of the Full Stokes (FS) equations. We use the HO approximation as it balances computational efficiency with thermomechanical 3D ice dynamics, including higher-order stresses and temperature-dependent viscosity, which are critical when simulating ice evolution over paleo-timescale. Although we recognise that FS offers greater accuracy in regions such as the grounding line, where the inclusion of bridging stresses, neglected in the HO approximation, are important, it remains computationally infeasible to use over extended timescales such as the Holocene. To better capture grounding migration, we run our HO model at resolutions of < 1km, following a model setup that is similar to Briner et al. (2020) and Cuzzone et al. (2022) which performed well when simulating both terrestrial and marine regions of the GrIS over the Holocene.

You discuss the Steensby Stade as the last part of the Holocene glacial history of North Greenland, and also discuss the late Holocene advance, which reached its maximum at the LIA. Are these the same advance – i.e. both culminated in the LIA? I think some clarity should be given about this – including the LIA limit. In Fig 2a you label the two previous Stades, and in Fig. 2b you have the LIA (offshore) limit labelled. Is this LIA actually limit actually recorded, I had a quick look at the Koch (1928) reference and couldn't see how this limit was recorded. Is there an onshore expression of the LIA too?

Thank you for raising this point. We are happy to clear up that the Steensby Stade, as described by Kelly and Bennike (1992), represents the re-advance of the GrIS from the mid-Holocene minimum to its recent maximum at the LIA. Regarding Koch (1928), there is a map show Ryder's extended ice tongue, its not possible to interpret the terrestrial extent of the ice clearly and is therefore not show in Figure 2. We have added text to our introduction and description of Ryder's Holocene behaviour to better describe the Steensby Stade and LIA.

<u>Text added to the introduction:</u>

Finally, the Steensby Stade characterises the neo-glacial re-advance of the GrIS from its Holocene minimum towards its most recent maximum in the Little Ice Age (LIA).

<u>Ryder's re-advance in the late-Holocene to LIA:</u>

The following lithologic facies after 3.9 ± 0.4 ka BP (LU2 and LU1), inline with the Steensby Stade described by Kelly and Bennike (1992), show a transition from open-water bioturbated sediments to laminated facies that indicate the regrowth and advance of Ryder's ice tongue towards the outer sill. Lauge Koch mapped Ryder's LIA extent in 1917 during the Second Thule Expedition, showing the ice tongue had extended toward the mouth of Sherard Osborn Fjord and the outer sill (Fig. 2b).

Younger Dryas spin up: you say that you are assuming that the Ryder Glacier was stable during the Younger Dryas. Is there any evidence to back this up? The YD in Greenland is very enigmatic, and there is often little evidence for a stillstand, moraine formation, or dramatic slowdown during it (unless I am mistaken). So, I'd slightly caution the statement that the glacier was stable at this point in time.

We appreciated the reviewer noting this it is a valid point to highlight how the YD was enigmatic and likely not consistent across GrIS, where large parts of the ice sheet had already retreated a fair distance from the shelf and in some cases into local fjords. Nevertheless, we would like to stand by our assumption that Ryder Glacier in particular appears stable during the YD. This stems from the oldest sediments in Sherard Osborn Fjord being dated to 12 ± 0.5 ka BP on the outer sill, which indicates Ryder was likely stable on the bathymetric high during the YD. It is also documented that retreat in the northern sector of GrIS was comparatively limited to other regions prior to the YD. We have included these points and extra references in our Spin Up section which we think helps ground out assumption that a YD spin up is acceptable and thank the reviewer for the comment.

New Spin Up Section:

We perform a Younger Dryas (YD) model spin-up to obtain an initial ice-sheet state that is both geologically consistent and internally coherent. We assume that Ryder Glacier remained stable during the YD, consistent with the earliest recovered sediments from Sherard Osborn Fjord (12 ± 0.5 ka BP), which indicate that the grounding line had not yet begun to retreat and was likely positioned on the outer sill (O'Regan et al., 2021). Although other sectors of the Greenland Ice Sheet (GrIS) began retreating from their Last Glacial Maximum (LGM) extents prior to the YD, retreat in the northern sector was comparatively limited (Leger et al., 2023). In this region, the grounding lines of major outlet glaciers remained stable at or near the fjord mouths, typically grounded on bathymetric highs, until the onset of early Holocene warming (Kelly and Bennike, 1992; England, 1999; Jennings et al., 2011; Jakobsson et al., 2018; Jennings et al., 2019; O'Regan et al., 2021).

We begin our spin-up simulations using an initial modern-day ice surface from BedMachine v5 (Morlighem et al., 2022) and force the model with a constant climate from 12,500 BP. We conduct a spin-up for the four different SMB scenarios…

L154: 12,500 BP until 2000 CE is 14,500 years, not 12,500.

Thanks for raising this, we understand why this brought up some confusion. We have defined P as being 1950, and added the following:

All model simulations are run for 12,550 years from 12,500 BP, where P is defined as 1950 CE, to 2000 CE…

P230: Is using the calving threshold for Petermann glacier here valid? Especially as the Petermann simulation was for present day conditions.

We are grateful that you highlighted this, and we recognise that the calibration of calving laws represents one of the largest current uncertainties in ice sheet modelling. To address this, we have amended in manuscript in two ways. Firstly, we tested our reference sigma_max threshold at the contemporary Ryder Glacier and found it was able to capture the recent change in terminus position well. This is show in the figure below which will be added to the Supplementary Information. Second, we have re-written the section in our Methodology where we discuss the calving thresholds. Here we discuss why a calving law calibrated to present day is likely not valid during the entire Holocene which is why we have used three different thresholds in our transient experiments.

Re-written Methods:

Our Reference calving threshold for floating ice is 300 kPa, this value was able to reproduce the recent evolution of Ryder Glacier's floating tongue (Fig. A1) and aligns with the threshold used in a study of the neighbouring Petermann glacier by Åkesson et al. (2022).

Because calving laws are often calibrated for glaciers in specific states, influenced by factors such as fjord geometry, bedrock topography, and ice rheology (Amaral et al., 2020; Wilner et al., 2023), we acknowledge that our chosen Reference calving threshold is unlikely to remain valid throughout the entire Holocene. To evaluate the influence of the calving threshold on ice dynamics, we conduct transient simulations with varied threshold values. For our High_Calving scenario, we lower the threshold to be 200 kPa …

<u>Additional calving threshold test:</u>

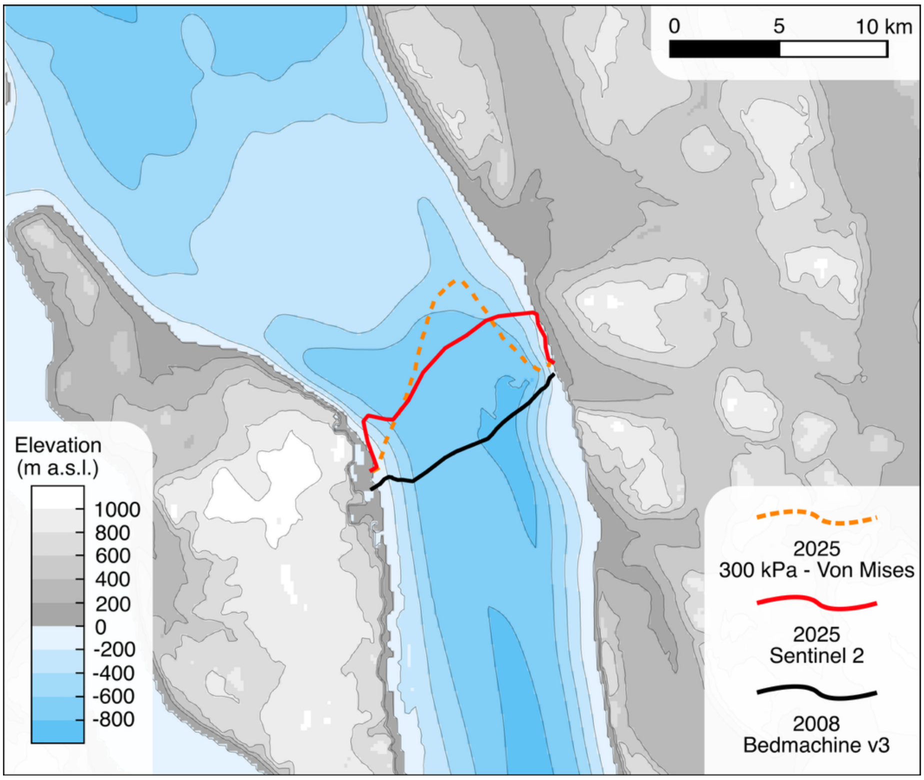

Figure A1. A comparison between the recent observed evolution of Ryder's calving front with a simulated front using the Von Mises Calving Law. The 2008 position of Ryder's terminus (black) is sourced from Bedmachine v3 (Morlighem et al., 2017) and is taken as the initial ice front position for our comparison simulation. The 2025 position of Ryder's terminus (red) is taken from a Sentinel 2 satellite image dated 19-05-2025. The simulated 2025 position of Ryder (dashed orange) uses the Von Mises calving law with a threshold of 300 kPa. Surface topography and ocean bathymetry are from BedMachine v5 (Morlighem et al., 2022).

Here we test whether the Von Mises calving law with σmax value of 300 kPa (Eq. 4), found to be a suitable tuning value for the neighbouring Petermann Glacier (Åkesson et al., 2022), reproduces the contemporary evolution of Ryder Glacier's terminus. To do this, we run our ice sheet model from the year 2008 forward to 2025 and compare the position of the ice front to observations. The initial ice front position and ice geometry are taken from Bedmachine v3 which has a nominal date of 2008 (Morlighem et al., 2017). Figure A1 shows the position of the observed front in 2025 against our simulated front using the Von Mises law with a σmax value of 300 kPa. The calving law reproduces the 2025 position well capturing the overall trend of glacier advance during the 17 years. While the centre of the ice tonuge terminus is slightly too advanced, the margins of the ice shelf, and their connection to the fjord walls which offer buttressing, terminate in a similar position to that observed in 2025.

Section 5.3 – the recent work on Nioghalvfjerdsbræ (79N) is partially included here (Smith et al. 2023), but further work has been completed here, in a similar setting (floating ice tongue collapse). Some further discussion of differences or similarities in forcings could be pertinent, as there is both offshore and onshore data.

Thank you for highlighting this, you are right to mention the new and interesting work being undertaken at 79N regarding its deglaciation from the continental shelf at the LGM to present day. We have added the modelling study of the Northeast Greenland Ice Stream by Tabone et al (2024) to our discussion on ocean melt rates that stress the importance of rising ocean temperatures in driving retreat from stable bathymetric positions.

L468: This may just be due to strange phrasing, but calving wouldn't have an impact on the terrestrial ice margin, unless you mean indirect impact in comparison to adjacent marine areas?

We appreciate you highlight this confusion, and note this was a similar comment to that raised by Reviewer #1. Our intention was to highlight how Cuzzone (2022) found the inclusion of calving and the resulting increase in inland thinning did not cause in the terrestrial margin retreat any faster. So, there was no **in-direct** impact on the terrestrial margin by including calving that thinned the interior. When re-reading the manuscript, we found that removing the discussion on terrestrial ice made the paragraph read better. Therefore, we now just talk about the similarities between our paper and Cuzzone (2022):

Cuzzone et al. (2022) note how the inclusion of calving allowed the marine margins to persist longer in the fjords, relative to adjacent terrestrial ice, due to a greater transport of mass from the interior, which in turn led to thinning in the upper regions of the domain. We find such consistencies across our simulations during the early Holocene, where, despite rapid retreat of the terrestrial ice, Ryder Glacier maintains an extended position in the fjord (Fig. 9).