Authors reply to Anonymous Referee

"Glacier inventories reveal an acceleration of Heard Island glacier loss over recent decades"

by L. G. Tielidze, et al.

EGUsphere

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Dear Referee,

Thank you very much for your comments which we help to increase the quality of our manuscript. Please find in the following a point-by-point reply to your review.

All corrections and changes we made in the text are marked up using the "Track Changes" function.

Best regards,

Levan Tielidze on behalf of all co-authors

The study by Tielidze et al. presents a comprehensive analysis of glacier changes on Heard Island over multiple decades, utilizing historical topographical maps and satellite imagery. The study effectively highlights trends in glacier retreat, debris cover evolution, and climate influences. However, certain aspects require further clarification and refinement to strengthen the conclusions drawn.

Thank you for positive feedback and please see our detailed comments below.

My major concern is about Stephenson Glacier. Figure 7: The digitised boundaries showing retreat and advancement using three lines for 2005-08-09 needs to be confirmed with more data. For me, the area depicted by 2009 and 2008 is resultant of calving of icebergs. Can you recheck this with more data? The authors mention a rapid lagoon formation, but how does this compare with similar cases elsewhere? Could lake expansion and calving instability be primary retreat drivers rather than just air temperature increases? Stephenson Glacier has lost debris cover over time, which contradicts the general trend. Why is this the case? Does this suggest significant ice thinning or enhanced calving?

We remapped Stephenson glacier terminus and reinterpreted its changes. We also updated figure 7 and 11.

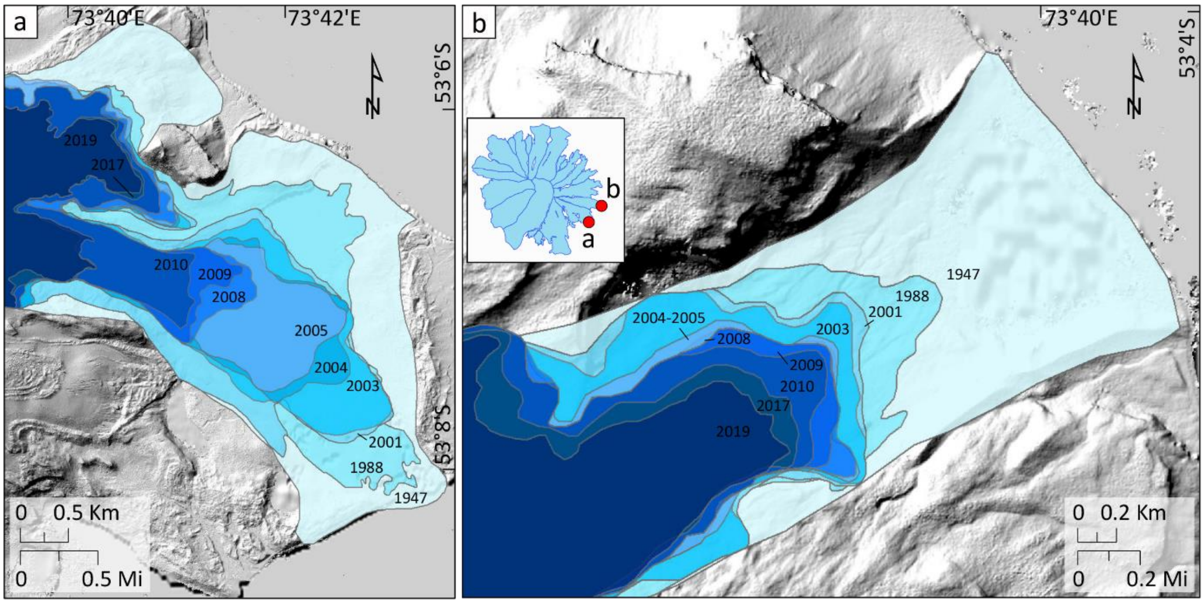

Figure 7. Stephenson (a) and Brown (b) glacier retreat between 1947 and 2019. Pléiades Hillshade is used as a background (07/04/2019). Insert map on panel 'b' shows location of the selected glaciers relative to other glaciers.

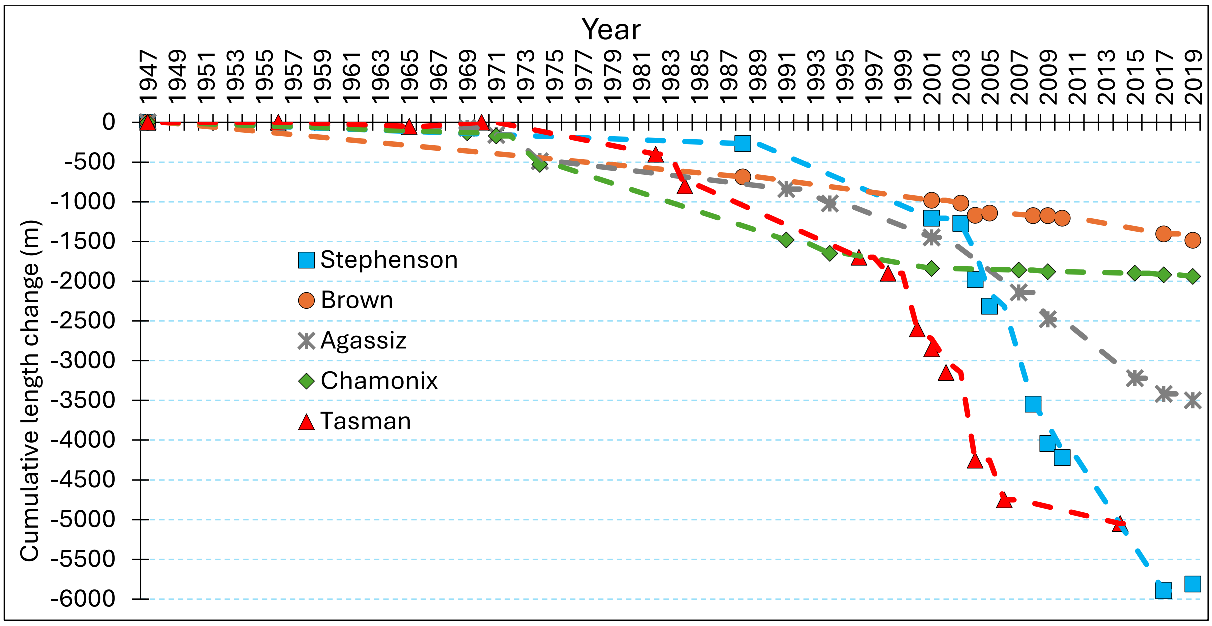

Figure 11. Cumulative length changes between 1947–2019 for Brown and Stephenson glaciers (current study) compared to Agassiz and Chamonix glaciers on Kerguelen (Deline et al., 2024) and Tasman Glacier in New Zealand (Purdie et al., 2020; Mackintosh et al., 2017).

'The retreat of Stephenson Glacier warrants further discussion. In the 1950s, the glacier had a steep and small accumulation area relative to its long (~5.5 km) and low angle terminus compared to its counterparts. A significant portion of that tongue was located near sea level (Figure 12). This is due to the subtle and flatter topography of eastern lower part of Heard Island (see also Figure 1c). This steep/small accumulation area, low angle terminus, relatively high ablation rates at sea level and melting by seawater and mechanical calving by tidal action (Truffer and Motyka, 2016) likely made the glacier more susceptible to warming. Once lagoon formation initiated, the high retreat rate of the Stephenson Glacier was enhanced by calving as the glacier retreated into its overdeepend basin. We also note that despite recent efforts to quantify water properties in similar environments (Mortensen et al., 2013; Straneo and Cenedese, 2015), rates of subaqueous melting for Heard Island glaciers along with the water properties of the associated lagoons are largely unknown and require further investigation.'

Line 25-27: The increase in debris cover from 7% to 12.8% is mentioned, but its implications for glacier mass balance should be briefly noted.

It would have been a speculative because our knowledge for debris cover and its implications for glacier mass balance is limited. We only present more evidence-based results.

Line 30-31: The phrase "many questions about the behaviour of Heard Island glaciers remain unanswered" is too vague. Specify which key uncertainties remain.

This sentence was deleted.

Line 239: Manual mapping is stated to be "more suitable" than automated methods. However, this should be qualified—manual delineation is more appropriate for small regions with significant debris cover, but automated methods may be effective for clean ice surfaces.

We edited this paragraph:

'Despite some advantages of the automated mapping method of clean ice (e.g. Paul et al., 2013), manual mapping of glaciers is more accurate for many mountain regions around the world (e.g. Stokes et al., 2013; Nagai et al., 2016; Tielidze and Wheate, 2018; Korneva et al., 2024). In this study, glacier boundaries were, therefore, delineated manually. This was also mainly due to the i) unavailability of cloud-free satellite channels/bands for different years for the entire study area, which limited us to use different band ratio segmentation methods for automated mapping; ii) significant amount of debris-cover, which can cause uncertainty during automatic mapping or hinder mapping; and iii) a relatively small study area, which was less time expensive than it would have been for an entire mountain range.’

Line 269: The uncertainty assessment should clarify whether multiple independent digitizations were conducted for validation.

We have carried out multiple digitizations. A new paragraph and figure have also been added:

‘To estimate glacier mapping uncertainty, first we tested multiple digitization (e.g. Paul et al., 2013; Tielidze et al., 2022). A sub-sample of two glaciers from the medium-resolution SPOT image, 1988, were re-digitized by three different operators. The selected glaciers included debris-free Brown and one unnamed debris-covered, glacier with Glims ID of G073625E53121S. The uncertainty for the debris-free Brown Glacier based on normalized standard deviation (NSD – delineations by multiple digitalization divided by the mean glacier area for all outlines) was 2.0 %. In contrast, the debris-covered glacier exhibited a much higher uncertainty of 5.3%. We applied the same methodology to these glaciers using the high-resolution Pléiades image from 2019. The mapping uncertainty for the debris-free glacier was determined to be 1.1%, while the debris-covered glacier exhibited a considerably higher uncertainty of 5.1% (Figure 3a-d).’

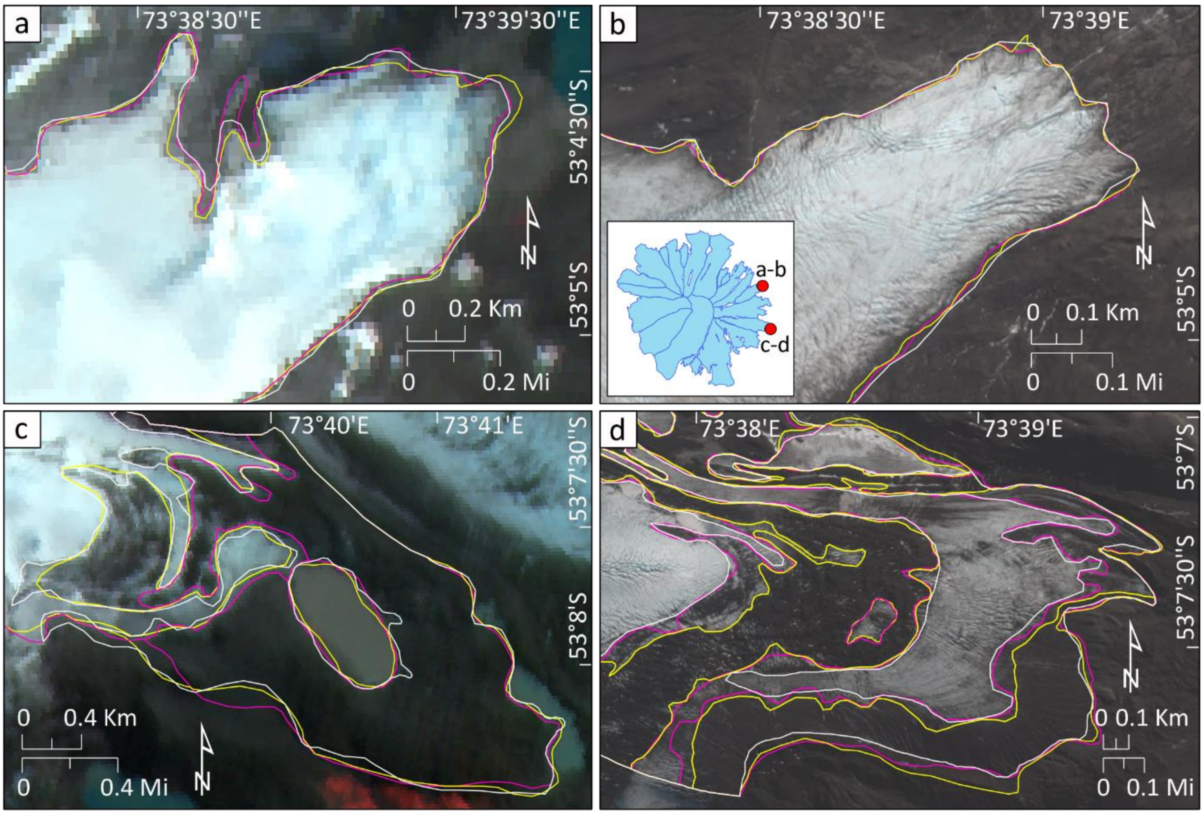

Figure 3. An example of multiple digitization for debris-free Brown (a-b) and debris-covered G073625E53121S (b-c) glacier terminus. a-c - SPOT scene (09/01/1988). b-d - Pléiades scene (07/04/2019). Insert map on panel 'b' shows location of the selected glaciers relative to other glaciers.

Line 251: Terminus measurements are described, but the frequency of available images (e.g., annual vs. decadal) should be stated explicitly.

We edited this paragraph:

'Accurately quantifying changes in glacier termini is essential for effective monitoring of glacier changes over various timescales, from years to centuries. Methods for this technique each offer advantages and limitations (Lea et al., 2014). In this study, we only measured two glacier (Stephenson and Brown) lengths based on the Global Land Ice Measurements from Space (GLIMS) guidelines (www.glims.com) and by following Purdie et al. (2014). The flow direction of the glacier was manually determined to be perpendicular to altitude contours. We assessed terminus changes by comparing glacier outlines from different dates along the ice front, oriented perpendicular to the flow. Elevation changes at the glacier fronts were also measured at the intersection points.'

Please also see Table 1 for all available images that were used for terminus measurements.

Fig. 3: The authors highlight higher retreat rates on the eastern side of Heard Island. Would it be possible to overlay temperature or precipitation data to visually reinforce this finding?

We updated Figure 3. Please see the new Figure 4.

We also note that instrumental measurements of temperature and precipitation are rare from Heard Island. Therefore, we use the ERA5 dataset, which is also not high enough resolution to overlay the western and eastern sides separately. Instead, we expanded the discussion to explain this process more clearly.

'We observed that higher rates of glacier retreat occurred on the eastern side of the island (Figure 4). Although climate data are sparse and a process-based modelling approach is required for further investigation, we expect this greater sensitivity of east-facing glaciers is due to orographic effects; satellite observations and limited climate station data show that the eastern side of the island, in the lee of the prevailing westerly winds, is less cloudy, warmer and receives less precipitation. This asymmetry has been noted in previous studies of Heard Island glaciers (e.g. Thost and Truffer, 2008) and is consistent with other islands in the sub-Antarctic region where strong westerly winds interact with mountain barriers. For example, Berthier et al. (2009) observed that the eastern part of Cook Ice Cap on Kerguelen shrank 2.5 times more (~28%) than the western part (~11%) between 1963 and 2003. Similar observations have been made in South Georgia, where glacier decrease on the east coast was higher than on the windy and wet southwest coast during the second half of the 20th century (Gordon et al., 2008).'

Line 403: The impact of decreasing surface albedo is mentioned, but cloud cover over Heard Island is persistent. Would reduced albedo have the same effect under high cloud conditions?

We deleted albedo and edited this paragraph:

'Maritime glaciers such as those on Heard Island are particularly sensitive to air temperature changes (e.g. Anderson and Mackintosh, 2006; Davies et al., 2014). Warming causes the frequent precipitation to fall as rain at higher elevation rather than as snow. Higher temperatures also increase melt rates due to strong turbulent exchange in these windy environments (e.g. Anderson et al., 2010; Anderson and Mackintosh, 2012). For these reasons, the observed summer temperature increases since 1980s are likely an important driver of ongoing glacier recession on Heard Island. However, few direct precipitation and mass balance measurements exist for Heard Island (Thost and Truffer, 2008), and Favier et al. (2016) showed that retreat of the Cook Ice Cap on the relatively nearby Kerguelen Islands is likely due to atmospheric drying since the 1960s rather than atmospheric warming. Further observations and modelling are required to increase confidence in our interpretation that climate warming was largely responsible for driving recent glacier retreat on Heard Island.'

Line 426: The discussion of human-induced warming should be carefully phrased. While anthropogenic climate change is a major factor, direct human interference on Heard Island is minimal.

We edited this paragraph accordingly:

'The warming trend evident in ERA5 data in the Heard Island region (0.7°C) is relatively small to the observed 1.1°C warming for the neighbouring Kerguelen Island between 1951-2020 (Nel et al., 2023) but it is in agreement with general Southern Ocean warming trend since 1950s (Auger et al., 2021; Li et al., 2023). Atmospheric and ocean warming in this region is associated with a shift towards the positive phase of the Southern Annular Mode (Pohl et al., 2021), including an intensification and poleward shift of the Southern Hemisphere westerly winds (Perren et al., 2020). This shift has been attributed to the combined anthropogenic effects of increasing greenhouse gases and decreasing stratospheric ozone (e.g. Son et al., 2008).'