

## Response to Anonymous Referee #1

We thank Anonymous Referee #1 for their considered review of our manuscript. Below we respond to each comment, with the referee's original comment shown in italic text and our response in blue text.

**Summary:** *This revised manuscript by Thompson and others focusses on some very detailed and important observations of the Shackleton-Denman system. They show that there has been very little structural change over the past 60 years and no obvious interannual variability in ice flow speeds over the past 20 years, with the exception of the floating section of Scott Glacier. I think these are important observations in the context of long-term change in this understudied section of the East Antarctic Ice Sheet, and I recommend publication in The Cryosphere. However, I do have a few relatively minor comments that are mainly focussed on wording surrounding the long-term changes across the Shackleton system that I think can be easily addressed/clarified.*

*Sustained change/long-term vrs short-term/major change – There are several sections in the manuscript that refer to the absence of a sustained long-term major change in the Shackleton system, many of which I have highlighted below. I appreciate there is an element of subjectivity in what exactly constitutes a sustained or major change, but I find it difficult to believe that a 15% acceleration since the 1970s, current grounding line retreat, inland thinning and mass loss does not constitute a sustained major change at Denman. I think this is just a case of re-wording some of these sentences. On some occasions, it is not clear if you are discussing the wider Shackleton system, or the Shackleton Ice Shelf.*

We thank Referee #1 for their considered comments and agree that the language used to describe change is subjective in places. We have re-structured and added to sections of the introduction, results, discussion and conclusion in response to detailed comment from Referee #2 (see below) and in doing so have ensured that we focus on the main the observations of this work and tried to avoid any subjective descriptions of change in the system. Throughout the whole manuscript we now refer to the Shackleton system as the region of observation of which the Shackleton Ice Shelf is a part of.

### *Minor comments*

*Line 26: “Over the 60-year period of observation, we find no evidence of either longer-term sustained change or significant annual or subannual variations in ice flow”*

*Long-term change in ice structure or ice speed, or both? I presume you mean ice structure because Denman has accelerated some 15% since the 1970s, but this is not clear because the previous sentence mentions ice velocities. Please clarify*

We have changed this section of the abstract to reflect our key observations, the section now reads

Line 24-33: Over the 60-year period of observation we find significant rift propagation on the Shackleton Ice Shelf and Scott Glacier and notable structural changes in the floating shear margins between the ice shelf and the outlet glaciers, as well as

features indicative of ice with elevated salt concentration and brine infiltration in regions of the system. Over the period 2017-2022 we observe a significant increase in ice flow speed (up to 50%) on the floating part of Scott Glacier, coincident with small scale calving and rift propagation close to the ice front. We do not observe any seasonal variation or significant change in ice flow speed across the rest of the Shackleton system.

*Line 28: "A previously mapped increase in the ice flow speed of the Denman Glacier is not observable beyond 2008". Unless I have missed it, I do not see anything in the main body that suggests previous literature has suggested an increase in flow speed of Denman Glacier post-2008? Or do you mean that other studies have observed an increase in flow speed of Denman pre-2008, but you observe no change post-2008. Please clarify and re-write appropriately.*

We have removed this sentence from the abstract to focus on our key observations.

*Line 72-75: Understand that this study has been published post-submission of this manuscript, but the below paper seems highly relevant here. You may wish to consider adding it to the discussion:*

*Herraiz-Borreguero & Naveira Garabato: Poleward shift of Circumpolar Deep Water threatens the East Antarctic Ice Sheet, Nature Climate Change, 2022*

We thank the review for highlighting this manuscript, we have a discussion of this to the section which now reads

Line 76-83: The high basal melt rates close to the grounding line in this region of Antarctica have been linked to a warming of up to 0.5 °C over the last 40 years that occurred in the open ocean off East Antarctica, concurrent with an even more pronounced warming of 0.8–2 °C observed over the continental slope (Herraiz-Borreguero and Naveira Garabato, 2022). This Circumpolar Deep Water (CDW) warming is linked to a poleward shift of the Antarctic Circumpolar Current's southern extent onto the Indian Ocean sector of the East Antarctic continental slope, in which the Shackleton Ice Shelf is located. The continental slope warming appeared strongest near ice shelves that are thinning or have retreating grounding lines such as the Denman Glacier (Herraiz-Borreguero and Naveira Garabato, 2022).

*Line 135: Its not clear to me what the shelf's "central front" is? I would try and be more specific here and refer to the "Shackleton Ice Shelf's central front". In my mind I immediately thought of Denman when I read "central front".*

We simply mean the front of the Shackleton Ice Shelf and have changed the sentence to clarify this, the sentence now reads

Line 154-155: Over the same time period, the front position of the Shackleton Ice Shelf advanced a total of 18 km with no obvious change in the annual rate of advance (Fig. 2a).

*Line 155: System 1 and system 2. Maybe clarify in the caption of Figure 1, the ‘1’ and ‘2’ in figure 1b refer to these rifts.*

We have added the rifts to the figure caption, now referred to as R1 and R2. The caption now reads

Line 628-630: Figure 1: (a) Area of focus in the regional context of the Aurora and Wilkes subglacial basins, location shown in inset (Background: BedMachine V2 (Morlighem et al., 2020)). (b) The Shackleton system overview in February 2021 with the two main rift systems on Shackleton Ice Shelf labelled R1 and R2. All features mapped from Sentinel 2A and 2B imagery acquired 05th – 27th February 2021.

*Line 245: “Over the ~ 60-year period of observation, the Shackleton Ice Shelf system has undergone observable variability in velocity and structure, but there is no sustained longer-term change.”*

*I disagree with the wording here. Denman has accelerated by some 15% since the 1970s and its grounding line is retreating. This is by definition a long-term change? Or are you solely referring to the Shackleton Ice Shelf here? To my mind “Shackleton Ice Shelf system” includes Denman, Scott etc, you even mention this in see line 47. I think this sentence needs to be re-worded/clarified.*

We have changed the structure and emphasis of the discussion section, this sentence now reads

Line 283- 286: Over the ~ 60-year period of observation, the Shackleton system has undergone observable variability in ice velocity and structure, although more frequent satellite observations in recent years have not revealed any distinct seasonal or annual cycles of variability across it. We discuss the observable changes by sub-system region, while considering their possible implications for the whole Shackleton system.

*Line 298-309: You may wish to include some discussion of the Herraiz-Borreguero paper here, it seems highly relevant in this paragraph discussion.*

We have changed the emphasis and structure of this section and included the work presented by Herraiz-Borreguero, the section now reads

Over the 60-year period of observation of the Shackleton system we observe significant rift propagation on the Shackleton Ice Shelf and Scott Glacier, and notable structural changes in the floating shear margins between the ice shelf and the outlet glaciers. Over the period 2017-2022 we observe a significant increase in ice flow speed (~ 50 % close to the ice front) on the floating part of Scott Glacier. Over the same time period we do not observe any seasonal variation or significant change in ice flow speed across the rest of the Shackleton system, and there is no observable change in the ice flow speed of the grounded ice or at the grounding line. However, given the likelihood of modified CDW (observed to be 0.8–2 °C warmer) accessing the shelf (Herraiz-Borreguero and Naveira Garabato, 2022), coupled with the observations that the outermost portions of Shackleton Ice Shelf experience the

most intense surface melt outside of the Antarctic Peninsula (Trusel et al., 2013), and a lengthening of the melt season (Zheng et al., 2018), the Shackleton system appears vulnerable to changes in both ocean and atmospheric forcing. Indeed, observed grounding line thinning and retreat (Brancato et al., 2020; Flament and Rémy, 2012) and localised ice flow speed change (Miles et al., 2021; Rignot et al., 2019) may indicate that the Shackleton system is already responding to changes in forcing. However, the timescales over which the system responds, and the implications of this response remain challenging to predict.

*Line 311-314: Again, I disagree with the wording here. Denman is flowing 15% faster than it did in the 1970s, its grounding line is retreating, there is evidence of inland thinning and the catchment is losing mass. I find it difficult to see how this is anything other than a sustained major change? I do think this needs to be re-worded.*

We have re-worded this section to reflect the changes we observe across the system and their possible implications, highlighting that the timescales over which the system responds to changes in forcing remain challenging to predict. The section now reads

Line 407-429: Indeed, observed grounding line thinning and retreat (Brancato et al., 2020; Flament and Rémy, 2012) and localised ice flow speed change (Miles et al., 2021; Rignot et al., 2019) may indicate that the Shackleton system is already responding to changes in forcing. However, the timescales over which the system responds, and the implications of this response remain challenging to predict.

We still do not have a clear picture of the cause of the 1972-2008 acceleration in ice flow speed of the Denman Glacier or indeed its later stabilisation. A previous calving cycle reconstruction indicated that a calving event at some point in the 2020s is highly likely (Miles et al., 2019) but from our observations we do not find any indication of when this may occur or the mechanism by which it may be initiated. In addition to thinning and induced dynamic changes there are several features of the system that could significantly speed up the response to external forcing. Such features include; (i) thinning suture zones; if the Masson Island suture zone on Shackleton Ice Shelf is thinning in response to ocean warming, the melange at the base of the suture zone will preferentially melt, promoting rift propagation and ice shelf break up (Kulesa et al., 2014; Larour et al., 2021; McGrath et al., 2014); (ii) shear margin weakening; the shear margins across the whole system are likely to weaken with increasing melt and elevated meltwater availability but in the region of the system from Scott Glacier towards Mill Island, potentially high salt concentrations in the ice could further enhance melt and increase deformation; (iii) brine infiltration; possible brine infiltration of the firn layers on Shackleton Ice Shelf could enhance fracture propagation and promote hydrofracture if there is an increase surface meltwater with the observed lengthening melt season; and (iv) subglacial conditions; heat flow anomalies in the region of the Denman Glacier are poorly resolved but recent multivariate analysis of available datasets indicate elevated geothermal heat flow ( $> 70\text{-}80 \text{ mW m}^{-2}$ ) to the west of the Denman region (Wilhelm II Coast) and in the Knox Basin interior (Stål et al., 2021). As observed elsewhere in East Antarctica, the deep trough beneath the Denman Glacier may favour vigorous channelisation of the subglacial meltwater system close to the grounding line (Dow et al., 2020) and

freshwater outflow into the sub-ice shelf ocean cavity could locally enhance basal melt rates near the grounding line (Jenkins, 2011; Wei et al., 2020).

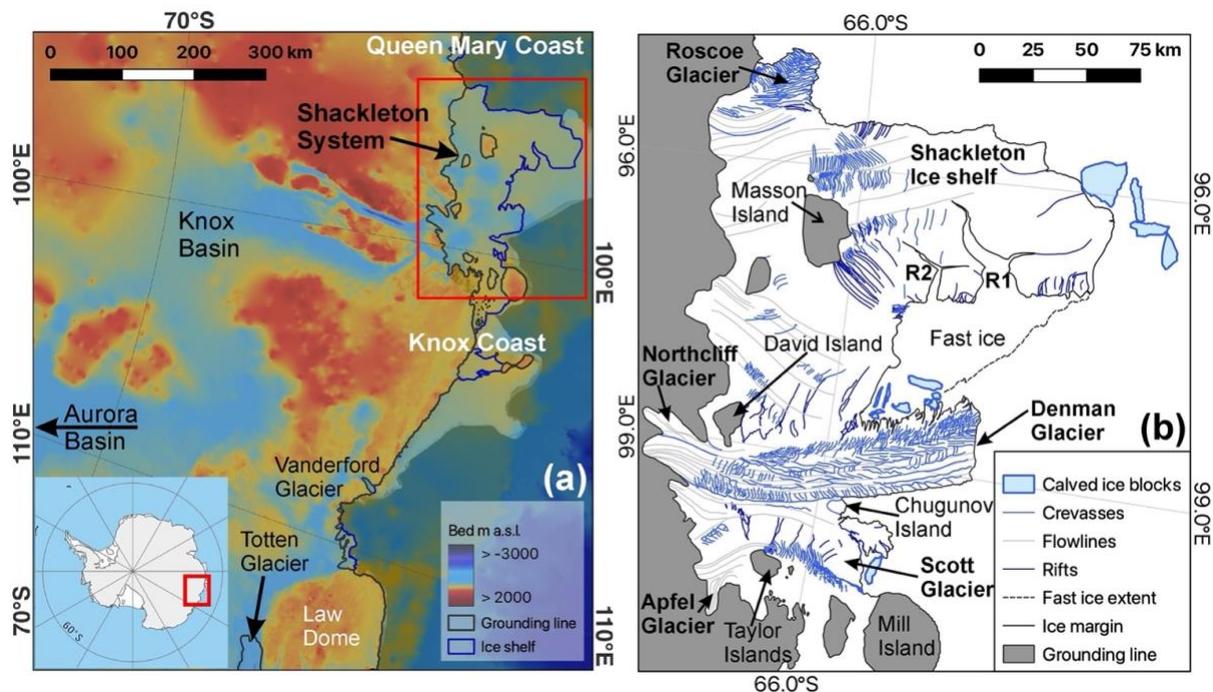
*Line 314: Short lived event – but it has been sustained? The glacier is still flowing faster than it did 50 years ago? It also could be argued the other way around, there has been a long period of acceleration, now there is a short-lived pause in acceleration. We do not know.*

We agree with the reviews concerns over the choice of language and have removed this sentence from the section. The first sentence of this paragraph now reads

*Line 411-412: We still do not have a clear picture of the cause of the 1972-2008 acceleration in ice flow speed of the Denman Glacier or indeed its later stabilisation*

Fig 1a) Moscow University is labelled in the wrong location. It is hard to see some of the labels, For example the blue labelling on the blue background. In general needs tidying up.

The figure are has changed to reflect the area of observation and all relevant features have been clearly labelled, see below

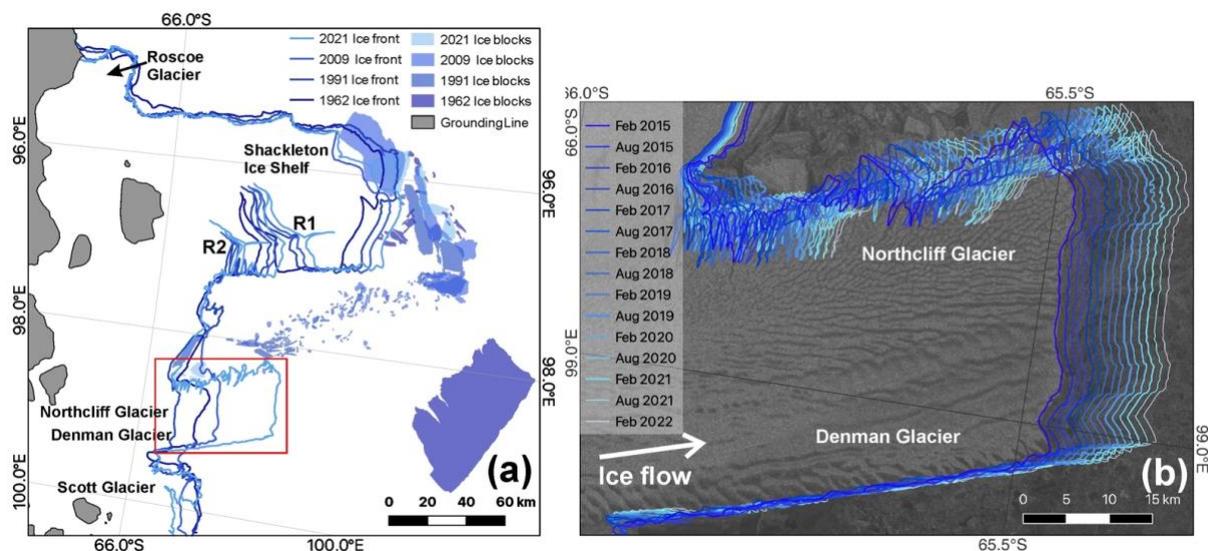


*Fig 2) I am sure it is just an issue with the PDF uploading, but please double check that the writing on the figures is not blurred when the final figures are submitted.*

This was due to the size of the document uploaded and we will ensure all figures are clear in the resubmission.

*Fig. 2b) It would look nicer if the date labels had some form of white/grey backing box. The black writing is hard to see on top of the dark SAR image. (Like you have done on Figure 4 for example)*

We have changed the figure labelling, see below



## Response to Anonymous Referee #2

We thank Anonymous Referee #2 for their considered and detailed review that has significantly improved the readability of our manuscript. Below we respond to each comment, with the referee's original comment shown in italic text and our response in blue text.

**Summary:** *This paper uses 60 years of satellite data and 6 ice penetrating radar transects to highlight changes in the ice structure and ice flow of the Shackleton Ice Shelf region, where results largely focus on the ice shelf, the well-studied Denman Glacier and the lesser analysed Scott Glacier. The results the authors present are important, and for the area outside of Denman Glacier, they are also novel – helping to characterise a poorly understood sector of Antarctica. I commend the authors on their hard work, as it must have taken a long time to find, collect, process and present the large amounts of data collated in this paper. However, I feel some of the hard work (evident in the methodology and figures) is lost within the text, which is quite poorly structured. The methodology is sound, and I do not propose any major changes to the manuscript, but I think the paper would benefit from more subheadings and a clearer structure. Below, you will find my main observations, listed as I work through the manuscript:*

1) *The introductory paragraph reiterates a lot about what we already know about the general state of the East and West Antarctic Ice Sheets. It should be more area specific.*

We agree that the paragraph needs to be more specific to the region of observation and have changed the text to reflect this. The paragraph now reads

Line 39-47: The East Antarctic Ice Sheet has historically been perceived as the stable sector of Antarctica (Silvano et al., 2016); however, it has now emerged that

the subglacial basins of Wilkes Land in East Antarctica have been contributing to sea level rise since the 1980s, with the Aurora subglacial basin contributing 1.9 mm (Rignot et al., 2019). The Shackleton system, fed by the Knox subglacial basin, is thought to be the most direct connection to the western portion of the Aurora subglacial basin (Fig. 1a). The Shackleton system is one of the largest ice shelf systems in East Antarctica and is comprised of a number of outlet glaciers including Denman, Scott, Northcliffe, Roscoe and Apfel. The floating component of the system is comprised of the Shackleton Ice Shelf together with the distinctive tongues of Denman-Northcliff, Scott and Roscoe glaciers, and an area of fast ice to the west of the Denman Glacier tongue (Fig. 1b). The Denman Glacier alone is estimated to hold an equivalent of 1.5 m of sea level rise equivalent ice mass (Morlighem et al., 2020).

*2) The rest of the introduction jumps around a lot. A more systematic study site description, noting glacier length, bed elevation, ice thickness (from BedMachine) would help to set up context for the paper.*

We agree that a more systematic approach is needed in the introduction and have added the suggested thickness/elevation descriptions to the second paragraph. The remainder of the introduction has been restructured to provide a more logical structure to describe the previous observations. The remainder of the introduction now reads

Line 49-98: Ice thicknesses across the grounded portion of the system range from ~ 400 m inland of Shackleton Ice Shelf to > 4000 m at the Denman Glacier (Morlighem et al., 2020). Bed elevations are also wide ranging with the main outlet glaciers grounded well below sea level and experiencing retrograde slopes (Brancato et al., 2020; Morlighem et al., 2020). Close to the grounding line ice thicknesses range from 300 m to 1400 m, thinning toward the ice front where ice thickness is in the range of 180 – 250 m with the exception of the front of the Denman Glacier tongue at ~ 450 m thick (Morlighem et al., 2020). Ice velocity data from the region are sparse before the late 2000s, but recent work identified an increase in ice velocity of the Denman Glacier of ~ 16 % since the 1970s (Rignot et al., 2019), with an increase of  $11 \pm 5$  % just upstream of the Denman Glacier grounding line between 1972-74 and 1989 and a more recent rate of acceleration of  $3 \pm 2$  % between 1989 and 2007-08 (Miles et al., 2021, their Fig. 3c). Analysis of Envisat data indicated that the Denman Glacier was thinning by 0.4 m year<sup>-1</sup> upstream of its grounding line between 2002 and 2010 (Flament and Rémy, 2012), and a  $5.4 \pm 0.3$  km grounding line retreat was detected between 1996 and 2017–2018 (Brancato et al., 2020).

The discovery of the deepest sub-glacial trough in Antarctica (>3500 m below sea level) beneath the Denman Glacier, with a gentle and slightly retrograde bed slope close to the grounding line (Morlighem et al., 2020), has prompted suggestions that the system may be vulnerable to marine ice sheet instability, potentially triggered by high basal melt rates in the ocean cavity just offshore the grounding line (Brancato et al., 2020; Morlighem et al., 2020; Rignot et al., 2019). Meltwater production from basal melt of the Shackleton system (73 Gt year<sup>-1</sup>) between 2003 and 2008 rivalled that from Thwaites (98 Gt year<sup>-1</sup>) (Rignot et al., 2013). Satellite derived basal melt rates between 2010 and 2018 revealed high but localised average basal melt rates of > 50 m year<sup>-1</sup> close to the Denman grounding line (Liang et al., 2021), on par with

basal melt rates in the Bellingshausen and Amundsen Sea (Adusumilli et al., 2020). Beyond the Denman Glacier grounding zone, there has been much less observation, although the surrounding Shackleton system has so far shown few signs of major dynamic change, with its flow restrained by islands, ice rises, and ice rumples (Stephenson et al., 1989; Young, 1989) (Fig.1). Much of the Shackleton system has an average basal melt rate of between 0 and 1 m year<sup>-1</sup>, with the exception of the Denman Glacier shear margins where refreezing in the order of 0.5 m year<sup>-1</sup> is indicated, as well as Roscoe Glacier where average basal melt rates away from the grounding line are 2-3 m year<sup>-1</sup> (Adusumilli et al., 2020; Liang et al., 2021).

The high basal melt rates close to the grounding line in this region of Antarctica have been linked to a warming of up to 0.5 °C over the last 40 years that occurred in the open ocean off East Antarctica, concurrent with an even more pronounced warming of 0.8–2 °C observed over the continental slope (Herraiz-Borreguero and Naveira Garabato, 2022). This Circumpolar Deep Water (CDW) warming is linked to a poleward shift of the Antarctic Circumpolar Current's southern extent onto the Indian Ocean sector of the East Antarctic continental slope, in which the Shackleton Ice Shelf is located. The continental slope warming appeared strongest near ice shelves that are thinning or have retreating grounding lines such as the Denman Glacier (Herraiz-Borreguero and Naveira Garabato, 2022). Although basal melt is considered the dominant form of melt related mass loss in East Antarctica, the outermost portions of Shackleton Ice Shelf in have been observed to experience the most intense surface melt outside of the Antarctic Peninsula (>>200mm w.e. year<sup>-1</sup>) (Trusel et al., 2013). There is also evidence that the Shackleton Ice Shelf may experience an increase in surface melting with an increase in the length of the melt season observed between 2002 and 2011 (Zheng et al., 2018). Circum-Antarctic studies have identified the Shackleton Ice Shelf as experiencing substantial losses due to thinning in recent decades (Greene et al., 2022) and a reported average thickness change of -3.4 m between 2010 and 2017 (Hogg et al., 2021).

Despite increased scientific scrutiny in recent years (Arthur et al., 2020; Brancato et al., 2020; Miles et al., 2021; Morlighem et al., 2020; Rignot et al., 2019; Stokes et al., 2019), existing data and knowledge are still insufficient to predict the future evolution of the Shackleton system with confidence. Aside from incomplete understanding of the dynamic controls on Denman Glacier flow and Shackleton Ice Shelf stability, almost nothing is known about the adjacent Scott, Northcliffe, Roscoe and Apfel glaciers or their shear margins. Here we add to the previously reported dynamic changes in the Denman Glacier over the 60-year period of observation and place them into the wider regional context of the Shackleton Ice Shelf system. We do so by also presenting an improved biannual temporal frequency of observations in the last seven years (2015-2022) integrating airborne radar data, new satellite observations of ice structure, changes in ice front position and ice-flow velocities, with known geometrical and glaciological constraints. We firstly report on the main structural features and dynamic changes across the whole system and then discuss the changes in the system and their possible impact by sub-system region.

*3) The ice penetrating radar methods section lacks detail - including important information like radar frequency and the applied ice velocity.*

The radar system transmits a frequency modulated chirped signal between 52.5 and 67.5 MHz and a constant ice velocity of 167 m/microsecond was applied to generate each radargram. We have added this information to the ice penetrating radar methods section, which now reads

Line 132-142: The ice-penetrating radar data presented here were acquired on two survey flights using the Snow Eagle 601 BT-67 aircraft (Cui et al., 2018) flown on 19 and 20 December 2018. The data were acquired using a radar system that is functionally equivalent to the High Capability Airborne Radar Sounder that has been described in the literature (Peters et al., 2007) and used in numerous studies of both grounded (e.g. Young et al., 2011) and floating ice properties and grounding zones (e.g. Greenbaum et al., 2015). The phase coherent radar system transmits a frequency modulated chirped signal between 52.5 and 67.5 MHz. The images presented in this manuscript reflect a postprocessing sequence that coherently adds 10 raw radar records at a time to increase signal to noise, applies matched filtering to account for the chirped transmit pulse, then incoherently stacks the resulting complex valued radar traces five times to suppress speckle noise. The ice bottom elevation data were computed using a semiautomatic approach involving manual localization above and below horizons of interest (the ice surface and ice bottom interfaces in this instance). A constant ice velocity of 167 m/microsecond was applied to generate each radargram.

*4) Remove general references to the “Queen Mary and Knox coasts”, replacing them with the Shackleton Ice System to reflect the focus of your paper (e.g. in the caption for figure 2). You must also refine your abstract and introduction to state which areas of your paper you will focus on. It sounds like you will analyse all glaciers, but you don't even mention the Northcliffe glacier in the text after the introduction!*

All references to Queen Mary and Knox Coasts have been removed from the text and the Shackleton system is used to refer to the region of observation (location shown in Figure 1) throughout the manuscript. Throughout the results and discussion, we have included descriptions of all the outlet glaciers where possible. We have also included area descriptions where no change is observable or a glacier is outside of the available data, for example we have no ice penetrating radar data over Roscoe Glacier.

*5) You talk about directions like north, east, south and west (e.g. in section 3.1 and figure 3) but as north isn't at the top of your figures it's not immediately intuitive what direction you're talking about. Can you also add remarks like inland and offshore as well, to quickly clarify directions (where suitable).*

We agree that this is confusing with the projection used in the figures. In all cases we have changed directions to inland / offshore or described locations in relation to other observed features, e.g., adjacent to Mill Island or adjacent to Chugunov Island.

*6) Refer to full glacier names in the text and figure captions (not simply 'Scott' – like the last word of paragraph 1 in section 3.1, and in the radar text of section 3.2)*

We have changed all references in text and figures to reflect the full glacier name.

7) *The results section isn't very systematic. Not every glacier is described in the same way, for example, there is no information provided about the Apfel Glacier even though you say you will discuss the whole Shackleton Ice Shelf System in the paper. It might be easier to break section 3.2 down further into sub-sections titled ice extent, rifts, strain rate etc. This will help readers interested in a specific component of the glacial system.*

We agree that subsections make the results much clearer to follow and have split the results into 6 subsections, (1) Ice front positions, (2) Rifts and crevasses, (3) Ice extent, (4) Shear margins, (5) Mean ice flow speed and strain rate and (6) Temporal change in ice flow speed. In each of the subsections we have described each of the glaciers of the system in turn or stated why this was not possible. The results section now reads

Line 144-278:

### **3 Results**

We have identified a number of dynamic and structural features of interest across the Shackleton system which we present in turn, describing changes in each of the following sections by sub-system region.

#### **3.1 Ice front positions**

Between 1962 and 2022, there is some small-scale variability (1-2 km) in the front position of Roscoe Glacier, but this is not consistent along the length of the ice front and there is no sustained change evident in the front position or the shape of the floating extent of Roscoe Glacier (Fig. 2a). Over the same time period, the Shackleton Ice Shelf's central front advanced a total of 18 km with no obvious change in the annual rate of advance (Fig. 2a). Calving occurred from the ice front of the Shackleton Ice Shelf, on the side adjacent to Roscoe Glacier in 1991, and a portion of the calved ice has since remained grounded just offshore of it (Fig. 2a). Between 2015 and 2022, the front of the Shackleton Ice Shelf then advanced steadily by  $\sim 0.3 \text{ km year}^{-1}$ . An iceberg from a calving event on the Denman Glacier, hypothesized to have occurred in the late 1940s ( $> 70 \text{ km}$  in length; Miles et al., 2021) is visible in 1962, roughly 100 km offshore the ice front (Fig. 2a). The Denman ice front position retreated in 1984 due to another major calving event (54 km in length; Miles et al., 2021). By 1991 the floating margin was still located 10-15 km south of the 1962 position but has since advanced  $\sim 63 \text{ km}$  (Fig. 2a). Over the time period 2015-2022, the Denman Glacier's ice front, which includes Northcliff Glacier, advanced at a rate of  $1.8 \text{ km year}^{-1}$  with a uniform pattern of advance and no seasonal variability in advance rate observed (Fig. 2b). The floating ice front of Scott Glacier has experienced more variability than that of Denman or Shackleton (Fig. 2a). Between 2015 and 2019, the front advanced at a steady rate of  $\sim 0.75 \text{ km year}^{-1}$  (Fig. 3a). Since 2020, small scale calving has been occurring on the side of the Scott Glacier adjacent to Mill Island, where the ice front position now lies  $\sim 5 \text{ km}$  inland of the 2015 front (Fig. 3b-d). In February 2022, the portion of the Scott Glacier ice front adjacent to Chugunov Island was in a similar position to that of 1962 but the whole ice front was  $\sim 10 \text{ km}$  further inland in 2009 (Fig. 2a, 3d). and in April 2022, a section  $>25 \text{ km}$  long calved from the Chugunov Island side of Scott (Fig. 4a). There is no clear margin between Scott Glacier and Apfel Glacier offshore of the Tylor Islands so we cannot comment on a distinct ice front position (Fig. 4a).

### 3.2 Rifts and crevasses

There is little observable change in surface structure on Roscoe Glacier with the exception of a rift opening in the vicinity of the margin with Shackleton Ice Shelf (Fig. 5). In 2022 the rift is 15 km long and 2 km wide at the widest point and extends to within 3.2 km of the ice front, a significant increase in dimensions of 5.3 km and 0.35 km, observable in 2015 when the feature terminated 8.5 km from the ice front (Fig. 5). Two major rift systems dominate on the Shackleton Ice Shelf, both of which extend into the ice shelf (labelled 'R1' and 'R2' in Fig. 1b) from the region of heavily fractured ice shelf ice, ~ 2,300 km<sup>2</sup> in size (Fig. 1b), held in place by fast ice and ~ 150 m thinner than the adjacent ice shelf body (Fretwell et al., 2013). System R1 is a maximum of ~ 15 km wide at the margin and extends over 40 km into the ice shelf, narrowing and eventually terminating at a spatially extensive suture zone that originates in the leeside cavity of Masson Island (Fig. 1b & 2a). A subsidiary rift branches off and connects with the ice shelf front (Fig. 2a). The geometry of system R1 has not changed significantly since 1962, although its width increased by ~ 5.3 km between 1962 and 1991 (Fig. 2a) and in 1962, there was no clear connection between the infant subsidiary rift and a front-parallel rift, visible by 1991 (Fig. 2a). System R2 is a maximum of ~ 5 km wide at the margin and extends into the shelf for 16.5 km, before branching into two rifts that trend in opposing directions, ~ 14 km and ~ 21 km in length respectively (Fig. 1b & 2a). System R2 changed more substantially than system R1, branching towards the grounding line and lengthening by 3.8 km between 2015 and 2022. In 1962 the rift is only visible as a crack, opening to a rift 2.3 km wide by 1991 and at the eastern edge, 4.5 km wide by 2017 (Fig. 1b & 2a). Between 1991 and 2015 the branch extending towards the grounding line increased in length from ~ 10 km to ~ 16 km and in width by ~ 1 km at the ice margin (Fig. 1b & 2a). The branch extending towards the ice front increased in length from ~ 13 km to ~ 16 km over the same time-period. Both systems advected with ice flow towards the ice front between 2015 and 2022, with no significant changes in shape (Fig. 2a). The surface of the Denman Glacier tongue is heavily fractured with a combination of crevasses, flow lines and channel-like features (Fig. 1b). However, there is a distinct difference in surface appearance across the width of the tongue (Fig. 2b). The ice originating from Northcliff Glacier on the Shackleton Ice Shelf side of the tongue, has a much higher spatial density of crevasses, while the ice originating from Denman Glacier is dominated by a combination of flowlines, channel-like features, and crevasses (Fig. 2b). A number of small rifts (< 6km long) are evident along the margin, separated by fast ice from Shackleton Ice Shelf and there is no identifiable change on the length or position of these rifts relative to the ice front between 2015 and 2022 (Fig. 2b). The floating portion of Scott Glacier is dominated by a series of rifts striking perpendicular to the flow direction (Fig. 4). The rifts initiate approximately 20 km down glacier of the grounding line (as defined by MEaSURES (Rignot et al., 2017)) and widen to ~ 2.5 km as they flow around the Taylor Islands. Between 2015 and 2022 the up-flow rift S1 widens at a rate of ~ 200 m year<sup>-1</sup> (Fig. 4a – labelled S1), while the down-flow rift S2 narrows at a rate of ~ 100 m year<sup>-1</sup> (Fig. 4a – labelled S2). The rift formation, widening and narrowing process is evident from 1962 through to 2009 (Fig. 4b). A rift on Scott Glacier, initiated from the shear margin on the Mill Island side of Scott Glacier, has increased in length toward Chugunov Island by ~ 5 km between February 2021 and June 2022 (Fig. 4c - labelled S3). There is no clear margin between Scott Glacier and Apfel Glacier

offshore of the Tylor Islands and no observable rifts on Apfel Glacier inland of the Tylor Islands (Fig. 4a).

### **3.3 Ice extent**

The ICECAP airborne radar lines flown in December 2016 provide a snapshot of information about the thickness and ice structure through the floating ice. The available airborne radar lines do not cover the Roscoe Glacier. The side of the Shackleton Ice Shelf adjacent to Denman Glacier thins from ~300 m thick, closer to the grounding line to ~150 m thick close to the Denman Glacier – Shackleton Ice Shelf shear margin (Fig. 7a), with a smooth, clearly defined ice base (Fig. 7b). A persistent near surface reflector is found in the Shackleton Ice Shelf region in all 6 radar lines, ~ 50 below the main surface reflector, at ~0 m asl in elevation (Fig. 7b). The Denman Glacier tongue consists of two distinct longitudinal sections with very different ice thicknesses, with the portion adjacent to Shackleton ~ 130-150 m thick and originating from Northcliff Glacier (Fig. 7a). The side of Denman Glacier tongue adjacent to Scott Glacier ranges from ~ 300 m to >500 m thick towards the central flowline (Fig. 7a), with the thickest parts of the tongue following the longitudinal features visible at the surface (Fig. 7a). In all 6 radar lines the Denman-Northcliff Glacier region shows significant surface and basal roughness (Fig. 7a). The Scott Glacier tongue has less variation in thickness across the width but thins from ~ 370 m thick in the vicinity of the first rift to ~ 150 m thick close to the ice front (Fig. 7a). The radar lines which extend beyond the Scott shear margin, towards the Taylor Islands and Mill Island appears dimmer, and the reflectors muted (Fig. 7b).

### **3.4 Shear margins**

Across the whole system, changes have been observed in the shear margins separating the various inlet glaciers and along the main body of the Shackleton Ice Shelf. Between 2015 and 2022, small changes are observable in the floating shear margin between the Shackleton Ice Shelf and Roscoe Glacier. As described in Section 3.3, a rift along the shear margin was observed to be three times the length and 10 times the width to that observed in 2015 (Fig. 5). There is no significant observable change in the floating shear margin between Shackleton Ice Shelf and Northcliff Glacier, visible surface features are advected toward the ice front with ice flow with little change in geometry (Fig. 1b). Over the same time period, small changes are observable in the floating shear margins on both sides of Scott Glacier (Fig. 6). The Scott Glacier shear margin that flows past the Tylor Island appears as a series of small rifts and crevasses, largely perpendicular to ice flow (Fig 6a-b). Over the 7-year period there has been lengthening of the features into the ice to both sides of the margin, as well as opening of existing features (Fig. 6a-b). The Scott Glacier floating shear margin that abuts the Denman Glacier is more clearly defined and has been widening into Denman Glacier in the vicinity of Chugunov Island (Fig. 6c-d). In 2015 this margin is relatively straight, in line with the floating margin of Denman and ~ 1.3 km wide. Notably, the shear margin appears to bulge progressively into Denman Glacier and is double the width by 2022 as compared with 2015 (Fig. 6c-d).

### **3.5 Mean ice flow speed and strain rate**

Mean ice speed derived at annual temporal frequency from Sentinel-1 data varies across the Shackleton System. In 2021, ice speed ranges from ~0.2 m day<sup>-1</sup> in the area between the grounding line and Masson Island on the Shackleton Ice Shelf to

~5 m day<sup>-1</sup> on the tongue of Denman Glacier (Fig. 8a). Surface ice speeds observed along Roscoe and Scott glaciers reach 1-2 m day<sup>-1</sup> and 2-3 m day<sup>-1</sup>, respectively. Inland of the junction with Denman Glacier, Northcliff Glacier ice flow speed is in the range of 1.5 m day<sup>-1</sup>, but once the two glaciers join there is no distinction between flow speeds (Fig. 8a). There are significant gaps in the coverage of Apfel Glacier, but observable values are in the region of 0.4 – 0.6 m day<sup>-1</sup> (Fig. 8a). The magnitude of the principal strain rate, derived from the mean velocity maps, highlights the shear margins of the Denman Glacier and Roscoe Glacier with the Shackleton Ice Shelf and the shear margins of the Scott Glacier (Fig. 8b), as well as four pinning points across the system (Fig. 8b). Pinning points have previously been identified at the front of the Roscoe Glacier and Shackleton Ice Shelf shear margin (label-a in Fig. 8b) and upstream of rift R2 on the Shackleton Ice Shelf (label-b in Fig. 8b, (Fürst et al., 2015)). There is evidence of two additional pinning points, Chugunov Island at the front of the Denman-Scott shear margin (label-c in Fig. 8b) and at the ice margin of Shackleton Ice Shelf (label-d in Fig. 8b). The latter coincides with a local topographic high in ocean bathymetry (Arndt et al., 2013).

### 3.6 Temporal change in ice flow speed

Recent changes in ice speed, derived by differencing the mean speed across the whole system between 2021 and 2018, are confined to the seaward ~ 60 km of the floating tongue of Scott Glacier and the Shackleton Ice Shelf (Fig. 9). On the floating portion of Scott Glacier increases of > 10 % occur across the outer 50 km (Fig. 9). The side of the Shackleton ice shelf closer to Denman Glacier, including the fast ice, appears to have decelerated over the same time period, where a change of between -4 % and -6 % is observed (Fig. 9). There is some evidence of deceleration on the side of the ice shelf closer to Roscoe Glacier, although the signal is unclear with values ranging between +/- 5 %. Annual ice speed percentage differences illustrate the increase in ice speed on the Mill Island flank of the ice front of Scott Glacier between 2017 and 2018 (Fig. 10a), which then appears to decelerate between 2018 and 2019, when a 4 % increase in the ice speed of the Chugunov Island flank of the ice front is observed (Fig. 10b). The increase in speed continues through 2019-2020 with a 10% acceleration from the ice front up to 45 km upstream and across the entire ice tongue width (Fig. 10c). The increase extends a further 15 km in the up-flow direction between 2020 and 2021 (Fig. 10d). There is more spatial variability in the annual speed percentage differences across the Shackleton Ice Shelf. The overall trend between 2018 and 2021 appears to be deceleration but there are small regions of acceleration and much of the variability is within the uncertainty bounds, thus complicating interpretation (Fig. 9).

Ice speed extracted from Sentinel-1 provides a timeseries between 2017-2021, which we extend back to 2002 using MEaSUREs (Mouginot et al., 2012, 2019; Rignot et al., 2011) and ITS\_LIVE (Gardner et al., 2018, 2021) in locations where available to highlight variability through time across the system (Fig. 9 and 11). Point locations on Shackleton Ice Shelf vary between ~ 0.2 m day<sup>-1</sup> at the grounding line (point 3 and 4 in Fig. 8b) and ~ 1 m day<sup>-1</sup> towards the front of the floating ice (point 2 in Fig. 8b), with no consistent temporal trends (Fig. 11a). Denman Glacier exhibits higher speeds, from < 2 m day<sup>-1</sup> upstream of the grounding line (point 5 in Fig. 9) to ~ 5 m day<sup>-1</sup> on the floating tongue (point 9 in Fig. 9) but speeds remain constant through time at each point location (Fig. 11b). Scott Glacier has a similar spatial pattern with speeds increasing from ~ 1.2 m day<sup>-1</sup> at the grounding line (point 10 in

Fig. 9) to  $> 4 \text{ m day}^{-1}$  close to the floating ice front (point 13 in Fig 9; Fig. 101c). There is no observable change in speed within 10 km of the grounding line of Scott Glacier (points 10 and 11 in Fig. 9; Fig. 11c). However, the downstream 30 km of the floating ice tongue show significant acceleration from January 2020 through to May 2021 (points 12 and 13 in Fig. 9; Fig. 11c). Over the 17-month period, ice speeds increase  $\sim 30 \%$  to  $2.5 \text{ m day}^{-1}$  30 km from the ice front (point 12 in Fig. 9) and  $\sim 40 \%$  to  $3.2 \text{ m day}^{-1}$  close to the front (point 13 in Fig. 9; Fig. 11c). Roscoe Glacier has similar ice speed spatial patterns to both Shackleton Ice Shelf and Denman Glacier, with slower speeds of  $\sim 0.4 \text{ m day}^{-1}$  at the grounding line (point 14 in Fig. 9), increasing to  $\sim 1.2 \text{ m day}^{-1}$  close to the floating ice front (point 16 in Fig. 9) and no significant change in speed through time (Fig. 11d).

8) *The ice flow section is clear and well written. I found this very helpful.*

Thank you

9) *The discussion isn't very well structured either. It begins by down-playing findings and then launching into radar findings, when it would make more sense to briefly outline how you're going to lay out the discussion, then follow that structure – by either discussing features in turn (as you do in the results) or describing changes by area (like the Denman glacier paragraph does). Many of your results, like ice front positions are not fully discussed, which acts to downplay your important results. Also, you fail to discuss some other important observations, like any distinct seasonal change. Why do you think there are no seasonal changes? Is this common in East Antarctica?*

We agree that the structure of the discussion was hard to follow and have restructured the section by sub-region, discussing all changes and possible implications by sub-region before discussing possible system wide implications and the open questions that full investigation of these implications pose. The discussion section is now separated into 4 subsections, (1) Roscoe Glacier, (2) Shackleton Ice Shelf, (3) Northcliff-Denman Glacier and (4) Scott-Apfel Glacier. We think there are no seasonal changes in ice flow speed because seasonal forcing observed elsewhere in Antarctica and in Greenland, such as seasonal changes in surface meltwater variability and seasonal sea ice break up reducing back stress, are currently insufficient to have an observable forcing effect on the Shackleton system. We have added an explanation of this to section 4.3 of the discussion below. The discussion section now reads

#### Line 279-392 : **4 Discussion**

Over the  $\sim 60$ -year period of observation, the Shackleton system has undergone observable variability in ice velocity and structure, although more frequent satellite observations in recent years have not revealed any distinct seasonal or annual cycles of variability across it. We discuss the observable changes by sub-system region, while considering their possible implications for the whole Shackleton system.

#### **4.1 Roscoe Glacier**

Roscoe Glacier is the only part of the Shackleton system where we do not observe any significant change in ice front position (Fig. 1b), despite consistent ice flow

speeds in the region of  $1 \text{ m day}^{-1}$  throughout the period of observation (Fig. 8, 11d). There is extensive crevassing visible at the surface (Fig. 1b) which could potentially facilitate high frequency, small scale calving if the features visible at the surface extended to depth. Additionally, the location of Roscoe Glacier at the margin of the system may mean that it experiences slightly different ocean forcing than the rest of the Shackleton System. Average basal melt rates of 2-3 m year over the floating region of the Roscoe Glacier is higher than much of the floating ice of the system away from the grounding zones (Adusumilli et al., 2020). Although no change in flow speed is evident over the period of observation, we do observe structural change at the shear margin with Shackleton Ice Shelf. A rift located along the shear margin both lengthened and widened since 2015 but has also been advected towards the ice margin with ice flow (Fig. 5). The effect of the feature is difficult to predict as the point at which the rift will intersect the ice front is the location of a pinning point (labelled 'a' in Fig. 8b), as previously identified by Fürst et al. (2015), who noted that the pinning point does not coincide with a topographic rise.

## 4.2 Shackleton Ice Shelf

The front of the Shackleton Ice Shelf is slowly advancing and changes in the geometry of the main surface features are restricted to the two main rift systems (Fig. 2a). The area of fast ice to the Denman Glacier side of the Shackleton Ice Shelf has decelerated by  $\sim 8 \%$  in the period 2018-2021 (Fig. 9). There is some evidence of deceleration across the rest of the Shackleton Ice but the change in speed varies between  $+6 \%$  and  $-8 \%$  over small areas indicating more significant uncertainty in the overall signal (Fig. 9). In 2021 flow speeds in this area of the ice shelf were in the region of  $1 \text{ m day}^{-1}$  so that the annual rate of deceleration over the 3-year period would only equate to  $\sim 10 \text{ m year}^{-1}$ . It is possible that the deceleration could be linked to reported thinning of the Shackleton Ice Shelf over the period 1997-2021 (Greene et al., 2022) but it contradicts instantaneous changes in velocity of  $+4 \%$  modelled in response to ice shelf thinning between 1994 and 2012 (Gudmundsson et al., 2019). The lack of significant rift propagation in rift system R1 on the main body of Shackleton Ice Shelf appears directly related to the Masson Island suture zone (Fig 2a). Indeed, there is growing recognition that the softer marine ice present in suture zones inhibits the growth of large-scale fractures, acting to stabilise ice-shelves by reducing local stress intensities (Kulesa et al., 2014; Larour et al., 2021; McGrath et al., 2014). While current observations suggest suture zones promote stability by halting rift propagation, a strong relationship between the thickness of ice mélange and the opening rate of the rifts has been observed, indicating that ice mélange thinning rather than ice shelf thinning can promote rift propagation (Larour et al., 2021). The increased sea water content and warmer temperature of the ice mélange suggests it may be more vulnerable to thinning due to future surface and basal melting than the surrounding meteoric ice, potentially affecting rates of rift opening and propagation (Kulesa et al., 2014, 2019; McGrath et al., 2014). Rift system R2 has undergone more significant change over the period of observation, although the rift tip does not appear to have reached the Masson Island suture zone (Fig. 2a) as yet and may experience a similar behaviour to that of R1 when it does. With prominent suture zones and pinning points as likely agents of stability (Kulesa et al., 2014, 2019), increased ice shelf thinning could lead to a significant calving event due to coincident suture zone thinning and further rift propagation, with unpinning of the ice shelf on the side of the Shackleton Ice Shelf adjacent to Roscoe Glacier ('d' in Fig. 8b). The relatively slow grounded ice flow speeds onshore of the

Shackleton Ice shelf suggests such a calving event is unlikely to initiate an increase in ice flow into the ocean, indeed it is considered passive in terms of ice buttressing (Fürst et al., 2016).

The persistent reflector at ~ 0 m asl in the airborne radar data over the Shackleton Ice Shelf (Fig. 7b) could be a result of strong melting and refreezing events observed on ice shelves elsewhere (Kuipers Munneke et al., 2017). These would lead to enhanced firn air depletion and are hypothesised to be a precursor to ice shelf collapse (Kuipers Munneke et al., 2014). Although, over the period of observation there is reportedly little evidence of an increase in visible surface melt or ponding area on Shackleton Ice Shelf (Arthur et al., 2020), there is some evidence of an increase in the length of the melt season (Zheng et al., 2018). An equally plausible interpretation of the bright reflector could be brine infiltration of the firn layer as this region lies within a zone thought to be susceptible to brine infiltration (Cook et al., 2018). Brine has been detected in firn cores from a number of Antarctic ice shelves (Heine, 1968; Kovacs et al., 1982; Risk and Hochstein, 1967; Thomas, 1975) and observed as a bright reflector close to sea level in radar data on the McMurdo (Campbell et al., 2017; Grima et al., 2016), Wilkins (Vaughan et al., 1993), Larsen (Smith and Evans, 1972), Brunt (Walford, 1964) and Ross ice shelves (Neal, 1979). Observations indicate brine infiltration may enhance fracture propagation and hydrofracture in ice shelves (Cook et al., 2018; Grima et al., 2016) and has been suggested to have contributed to the disintegration of the Wilkins Ice Shelf in West Antarctica (Scambos et al., 2009). Although both suggestions are plausible at this location, current observations are insufficient to conclusively identify the most cause of the reflector and therefore the impact of the evolution of the system.

### **4.3 Denman-Northcliff Glacier**

What has been referred to as the Denman Glacier tongue is comprised of two distinct ice masses originating from the Northcliff and Denman Glaciers. The whole of the floating region of the Denman-Northcliff Glacier appears to behave dynamically as a single unit, exhibiting the same ice flow speed (Fig. 8, 9, 10, 11), despite significant differences in ice thickness (Fig. 7) and surface crevasse frequency (Fig 2b). The ice originating from both the Denman and Northcliff Glaciers exhibits significant basal roughness (Fig. 7), which has been cited to significantly influence heat and salt exchange at the ice-ocean interface (Watkins et al., 2021). The acceleration in ice flow speed observed just upstream of the Denman Glacier grounding line between 1972-4 and 1989 and, to a lesser extent, through to 2008 (Miles et al., 2021, their Fig. 3c) is not observable post 2008 (Fig. 11b) and we do not identify any changes in surface structure to provide insight as to the cause of the acceleration. The ice flow speed of the Denman-Northcliff Glacier has been constantly ~ 5 m day<sup>-1</sup> close to the ice front over the period 2015-2022, with a uniform flow direction and no observable seasonal variability in flow speed (Fig. 2b, 8a, 11b). While efficient meltwater surface-to-bed connections via moulins and fractures are common in the Greenland Ice Sheet and seasonal changes in surface meltwater variability have been observed to cause seasonal changes in ice flow speeds (Hoffman et al., 2018; Sundal et al., 2011), there is currently very little evidence for coupling between the surface and basal hydrological systems in Antarctica (Bell et al., 2018). However, season variations in ice flow speed have been observed on an outlet glacier in East Antarctica, coincident with seasonal sea ice break up reducing back stress on the system and the onset of seasonal melt thought to weaken the shear margins (Liang et al., 2019). Our results suggest that

seasonal variation in sea ice extent or surface melting are currently insufficient to have an observable forcing effect on the Shackleton system.

#### 4.4 Scott-Apfel Glacier

Scott Glacier has received less attention until now, being thinner and slower than Denman Glacier, with an overall decrease in velocity observed between 1972-4 and 2016-7 (Miles et al., 2021). However, this part of the system is where we observe more variability (Fig 4, 6, 7, 8, 9, 10, 11). We observe the ice front of Scott Glacier to be in a similar position in 2009, 2002, 1991 and 1962 (Fig. 2a, 3), but the ice front may have experience retreat inland of this position in the intermediate time periods. However, the ice front position observed in June 2022 (Fig. 4a) is further inland than any previous observations, only marginally so adjacent to Mill Island but by ~ 18 km adjacent to Chugunov Island, with the calving of a 27 km long block in April 2022 (Fig. 4a). Furthermore, the recent > 5 km extension of rift S3 on Scott Glacier leaves only ~ 6 km of heavily crevassed ice between the S3 rift tip and a small rift that initiates at the ice front at Chugunov Island (Fig. 4a). If rift S3 continued to propagate and the region of ice offshore of the rift calved, the effect of Chugunov Island as a pinning point (labelled in C in Fig. 8b) could be reduced. The observed changes in ice front position of Scott Glacier are coincident with a doubling of ice flow speed at the ice front, from 2 m day<sup>-1</sup> in January 2020 to 4 m day<sup>-1</sup> in January 2022 (Fig. 11c). The increase in ice flow speed extends from the ice front to rift S1 but is not observable inland of this feature, suggesting that the acceleration is being initiated on the floating ice rather than related to any changes at the grounding line. While rift S1 on Scott Glacier has experienced an increase in width in recent years, the rate of change has remained constant at ~200 m year<sup>-1</sup> between 2015 and 2022 (Fig. 4). We currently do not have enough information to determine causation and therefore to predict future change on Scott Glacier, but it does coincide with instantaneous changes in velocity of +8 % modelled in response to ice shelf thinning between 1994 and 2012 (Gudmundsson et al., 2019). It would be reasonable to expect a continuation of higher flow speeds or a further increase in ice flow speed on the section of Scott between rift S1 and the ice front if the glacier tongue became unpinned from Chugunov Island. Further investigation is needed to determine the extent to which changes on Scott Glacier tongue impact on the adjacent Denman tongue, as the change in the geometry of the shear margin between Scott Glacier and Denman Glacier (Fig. 6c-d) is coincident in time with the changes in ice front position and flow speed of this section of Scott Glacier.

The muted reflectors in the radar lines that extend past the Scott Glacier shear margin adjacent to Mill Island (Fig. 7) may indicate that the extremely high salt concentration found in the Mill Island ice core (Inoue et al., 2017) extends from Mill Island up-flow towards the grounding line (Fig. 7a). High salt concentrations in ice facilitate mechanical deformation, enhancing grain boundary sliding as well as reducing the melting temperature of ice (De Almeida Ribeiro et al., 2021). If the muted reflectors identified (Fig. 7b) are in indication of high salt concentration, any changes in atmospheric or ocean forcing could have an enhanced impact on this region of the Shackleton system. No changes in structure or ice flow speed are observed up flow of the large rift to the west of the Taylor Islands (Fig. 4c – labelled 1), and the acceleration does not currently appear to have any connection to the grounded ice (Fig. 9, 11c). Surface meltwater features, reported to be frequent around the Scott and Apfel grounding lines, do not appear to be increasing in area or

frequency between 2000 and 2020 (Arthur et al., 2020) and are unlikely to be contributing to the changes observed on Scott Glacier.

*10) The discussion section also contains a lot of results based text, which is presented as almost stand-alone text which isn't used to evidence a discussion.*

We have moved any stand-alone results-based text to the results section and only described results to evidence the discussion. Please see the response to point 9 for more detail.

*11) The conclusions don't summarise all the results. They should contain more information on your important findings about rift propagation and shear margin changes as these could be explored further in future work (in detailed models for example) – which would use all the data you have so carefully collected and presented. This is much more important to report than your concluding remarks about needing more data, in a very generic sense.*

We have added to and restructured the conclusions to emphasise all of our results in the context of existing work and presented directed future research priorities. The conclusions now read

#### Line 394-434: **5 Conclusions**

Over the 60-year period of observation of the Shackleton system we observe significant rift propagation on the Shackleton Ice Shelf and Scott Glacier, and notable structural changes in the floating shear margins between the ice shelf and the outlet glaciers. Over the period 2017-2022 we observe a significant increase in ice flow speed (~ 50 % close to the ice front) on the floating part of Scott Glacier. Over the same time period we do not observe any seasonal variation or significant change in ice flow speed across the rest of the Shackleton system, and there is no observable change in the ice flow speed of the grounded ice or at the grounding line. However, given the likelihood of modified CDW (observed to be 0.8–2 °C warmer) accessing the shelf (Herraiz-Borreguero and Naveira Garabato, 2022), coupled with the observations that the outermost portions of Shackleton Ice Shelf experience the most intense surface melt outside of the Antarctic Peninsula (Trusel et al., 2013), and a lengthening of the melt season (Zheng et al., 2018), the Shackleton system appears vulnerable to changes in both ocean and atmospheric forcing. Indeed, observed grounding line thinning and retreat (Brancato et al., 2020; Flament and Rémy, 2012) and localised ice flow speed change (Miles et al., 2021; Rignot et al., 2019) may indicate that the Shackleton system is already responding to changes in forcing. However, the timescales over which the system responds, and the implications of this response remain challenging to predict.

We still do not have a clear picture of the cause of the 1972-2008 acceleration in ice flow speed of the Denman Glacier or indeed its later stabilisation. A previous calving cycle reconstruction indicated that a calving event at some point in the 2020s is highly likely (Miles et al., 2019) but from our observations we do not find any indication of when this may occur or the mechanism by which it may be initiated. In addition to thinning and induced dynamic changes there are several features of the system that could significantly speed up the response to external forcing. Such features include; (i) thinning suture zones; if the Masson Island suture zone on

Shackleton Ice Shelf is thinning in response to ocean warming, the melange at the base of the suture zone will preferentially melt, promoting rift propagation and ice shelf break up (Kulesa et al., 2014; Larour et al., 2021; McGrath et al., 2014); (ii) shear margin weakening; the shear margins across the whole system are likely to weaken with increasing melt and elevated meltwater availability but in the region of the system from Scott Glacier towards Mill Island, potentially high salt concentrations in the ice could further enhance melt and increase deformation; (iii) brine infiltration; possible brine infiltration of the firn layers on Shackleton Ice Shelf could enhance fracture propagation and promote hydrofracture if there is an increase surface meltwater with the observed lengthening melt season; and (iv) subglacial conditions; heat flow anomalies in the region of the Denman Glacier are poorly resolved but recent multivariate analysis of available datasets indicate elevated geothermal heat flow ( $> 70\text{-}80\text{ mW m}^{-2}$ ) to the west of the Denman region (Wilhelm II Coast) and in the Knox Basin interior (Stål et al., 2021). As observed elsewhere in East Antarctica, the deep trough beneath the Denman Glacier may favour vigorous channelisation of the subglacial meltwater system close to the grounding line (Dow et al., 2020) and freshwater outflow into the sub-ice shelf ocean cavity could locally enhance basal melt rates near the grounding line (Jenkins, 2011; Wei et al., 2020).

The potential vulnerability of the Shackleton system to increasing atmospheric and ocean forcing, the magnitude of potential sea level rise of the Denman Glacier alone ( $\sim 1.5\text{ m}$ ) (Morlighem et al., 2020) and the potential link to the Aurora Subglacial Basin (through the Knox Basin) make this region of East Antarctica one of significant importance in improving predictions of sea level rise. Critical to assessing the timing and magnitude of sea level rise contributions are improvements in the measurement of ice cavity bathymetry, subglacial conditions, and the evolution of surface melt water systems, as well as targeted collection of field data to allow better incorporation of features such as suture zones, pinning points and brine infiltration into numerical models of ice shelves.

*12) The Data Availability statement doesn't mention the radargrams. If they aren't freely available to download online, can they be requested from the data collectors? Also mention the BedMachine database used in Figure 1.*

The radar-based ice bottom elevation data and radargrams presented here will be published to the Australian Antarctic Data Centre (<https://data.aad.gov.au/>) upon publication. We have added this statement, as well as BedMachine, to the data availability statement, which now reads

**Line 445-452: Data availability**

All satellite imagery used in this work are freely available as follows; Landsat 8 OLI, 5 TM and 1 (all downloaded from <https://earthexplorer.usgs.gov/>), MODIS Mosaic of Antarctica 2008-2009 (downloaded from <https://nsidc.org/data/nsidc3350593/versions/2>), Sentinel 2 A and B (all downloaded from <https://scihub.copernicus.eu/dhus/#/home>) Sentinel 1A and B GRD (all downloaded from <https://scihub.copernicus.eu/dhus/#/home>) and ARGON KH-5 (downloaded from <https://earthexplorer.usgs.gov/>). BedMachine (v2) data is freely available (<https://nsidc.org/data/nsidc-0756/versions/2>). The radar-based ice bottom elevation data and radargrams presented here will be published to the Australian Antarctic Data Centre (<https://data.aad.gov.au/>) upon publication.

Suggested figure changes are below (note that all figures appear blurry, but I presume this is a result of copying and pasting):

The quality of the figures was reduced to keep to the file upload size limits, we will make sure all of the figures are of sufficient quality and clarity when uploaded in this revision.

Figure 1

- Why is the area in panel a so zoomed out? I'd focus in more on the area you examine, maybe just extending as far south as Law Dome so you can really see the detail of the bed topography in your study area.

We have changed the regional focus of the figure. See below

- In panel b could you make the glacier names stand out in bold as these are key points

All of the glacier names are now in bold, see below

- In the caption mention that numbers 1 and 2 refer to rift systems.

We have described rifts R1 and R2 in the caption, see below

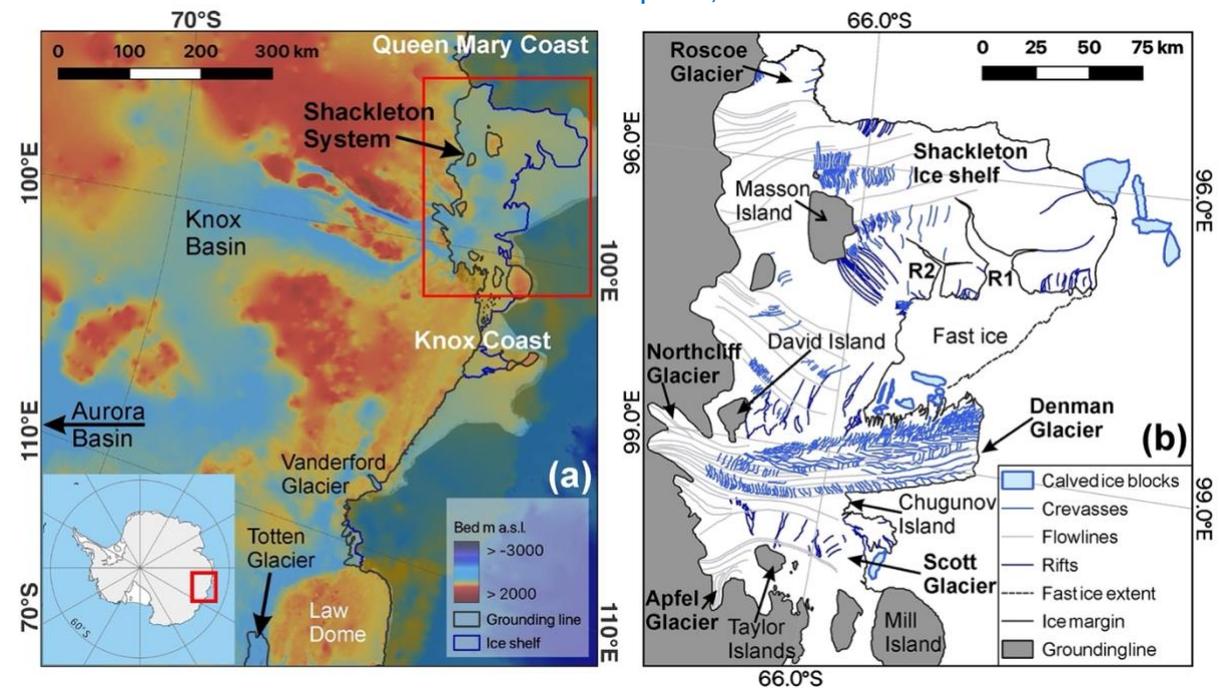


Figure 1: (a) Area of focus in the regional context of the Aurora and Wilkes subglacial basins, location shown in inset (Background: BedMachine V2 (Morlighem et al., 2020)). (b) The Shackleton system overview in February 2021 with the two main rift systems on Shackleton Ice Shelf labelled R1 and R2. All features mapped from Sentinel 2A and 2B imagery acquired 05th – 27th February 2021.

Figure 2

- Please add glacier names to panel a to make the figure more useful

We have added the glacier names, see below

- Add rift numbers to panel a too, to help the text in section 3.2

We have added the rift number to panel a, see below

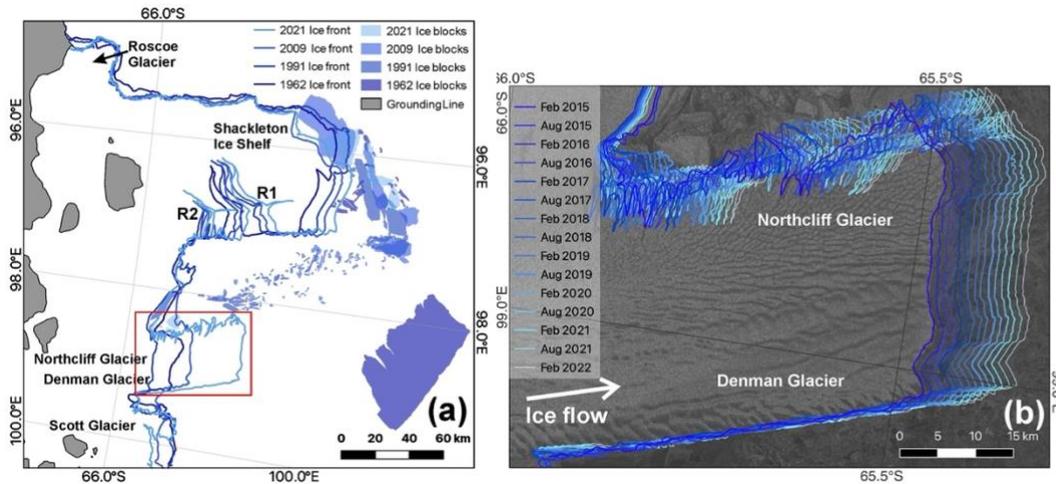


Figure 2: (a) Ice front positions of the Queen Mary and Knox coasts since 1962, including the large iceberg hypothesised to have calved from the Denman tongue in the 1940s. Position and blocks mapped from 16th May 1962 – ARGON KH5, 10th - 12th February 1991 – Landsat 5 TM, 1st November – 28th February 2009 – Modis MOA (Scambos et al., 2007) and 5th – 27th February 2021 – Sentinel 2A and 2B. The two main rift systems on the Shackleton Ice Shelf are labelled 1 and 2. (b) Denman Glacier biannual ice front position mapped in February and August from 2015 through 2022 (Background: Sentinel 1a acquired 27th February 2015).

### Figure 3

- Change caption to say “Scott Glacier”.

We have changed the caption to Scott Glacier, see below

- Add glacier name to figure.

The glacier name has been added to the figure, see below

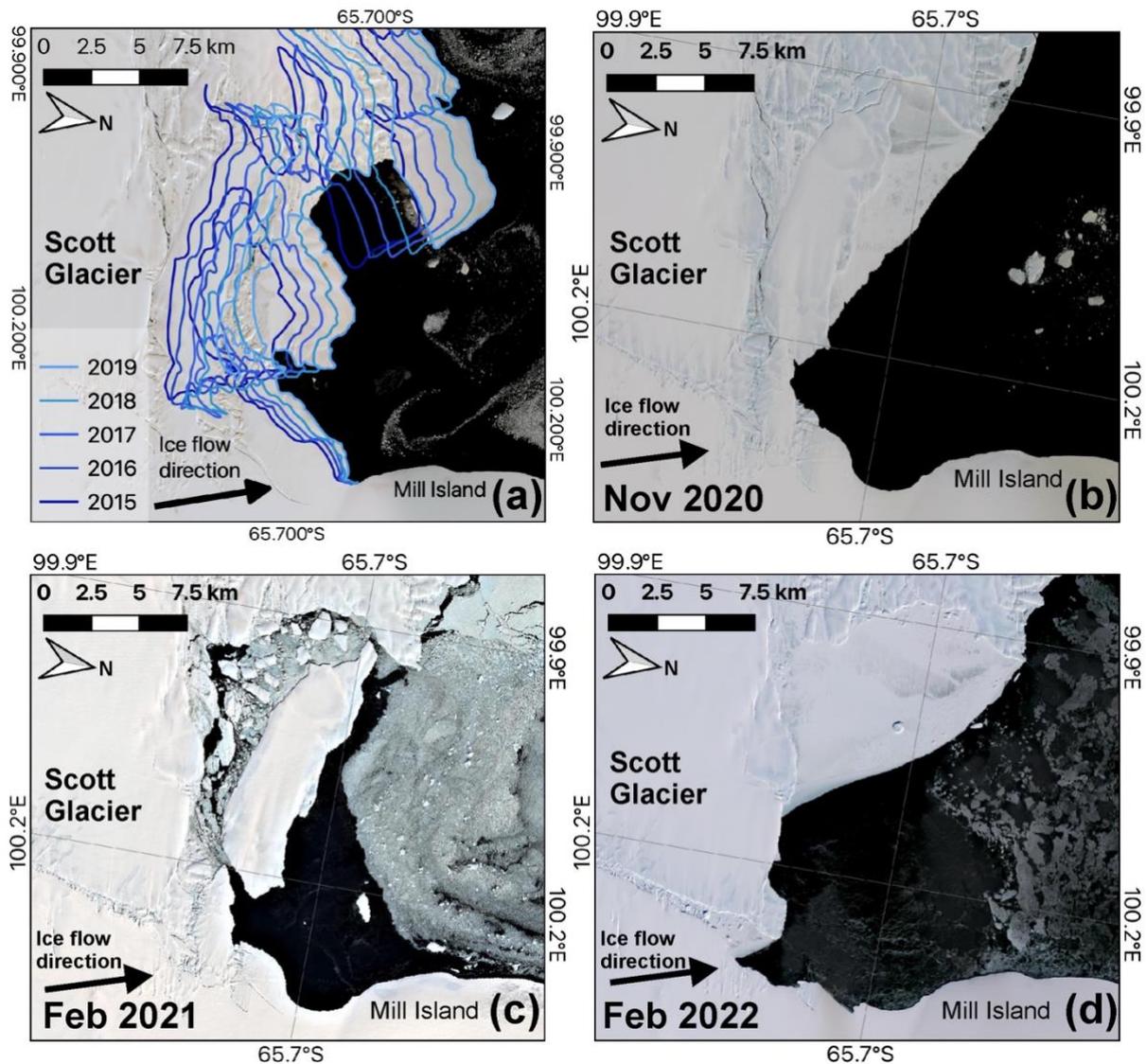


Figure 3: (a) Scott Glacier ice front position between 2015 and 2019 mapped from Landsat 8 OLI acquired on 16th February 2019, 1st February 2018, 24th February 2016 and 7th February 2015 and from Sentinel 2A acquired on 23rd February 2017 (Background: Landsat 8 OLI – 16th February 2019). (b) Scott Glacier ice front 26th November 2020, the central portion of the front has lost some of the blocks held in place by fast ice and an area immediately to the south of Mill Island (Landsat 8 OLI), (c) Scott Glacier ice front 27th February 2021, the fast ice has broken up and a larger block is separated (Sentinel 2B), (d) Scott Glacier ice front 21st February 2022, (Sentinel 2B).

#### Figure 4

- Could you label the rifts differently to those already identified as rifts 1 and 2 elsewhere to avoid confusion? Maybe S1, S2 and S3 here, and D1 and D2 previously?

The rifts have been labelled S1-S3, see below

- Does the arrow point to North? If so, it should say N.

The arrow does point north and has been labelled, see below

- Write out glacier names in full on panel c, so Scott Glacier etc. The same should be done for Figure 7.

The glacier names have been added in panel c (now a) and to Figure 7, see below

- *In the caption put the acquisition dates in brackets*

Have added the brackets to the acquisition dates, see below

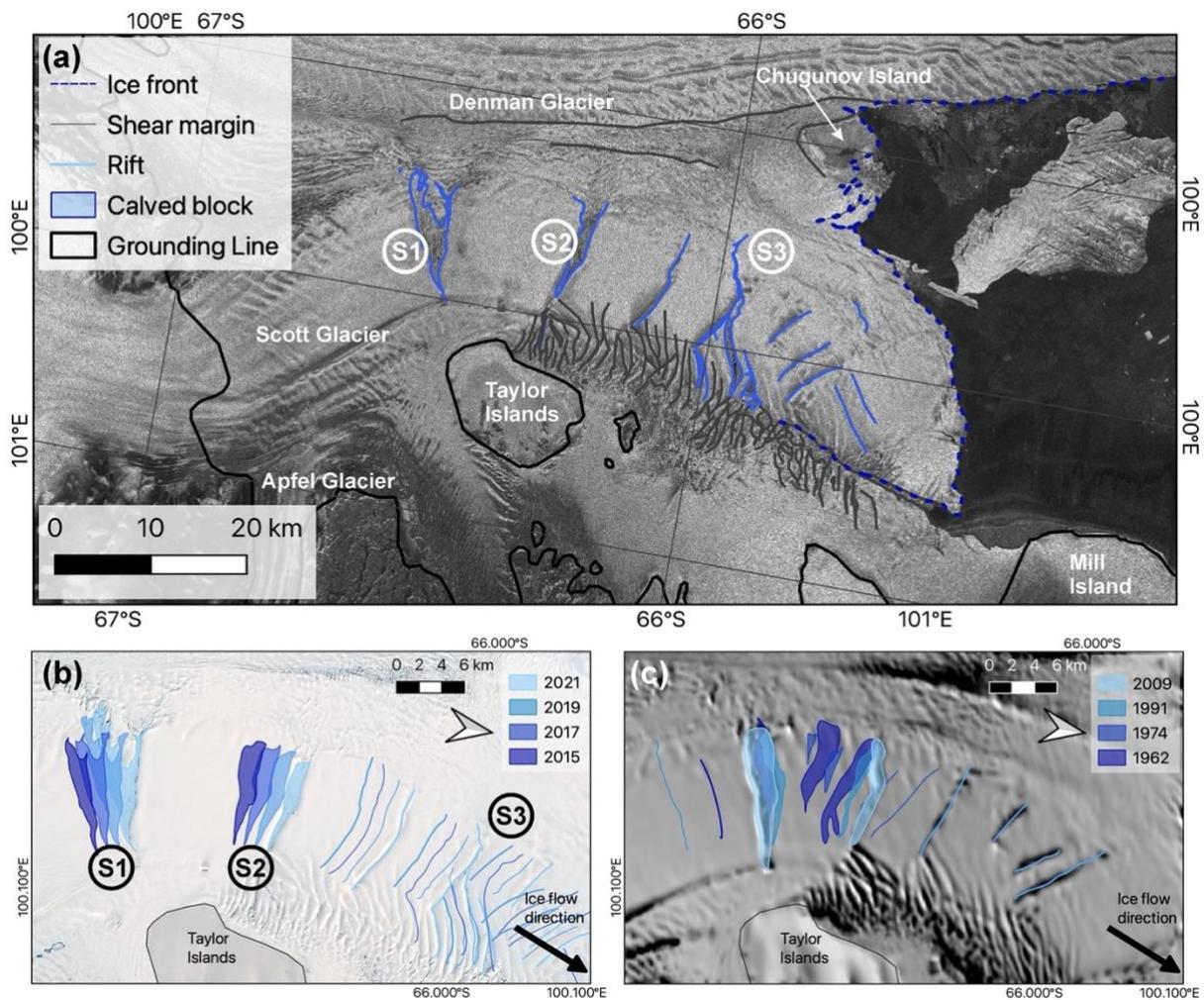


Figure 4: Evolution of the rifts on Scott Glacier from (a) 2015-2022 mapped from Sentinel 2B (acquired 27th February 2021), Landsat 8 OLI (acquired 16th February 2019 and 25th March 2015) and from Sentinel 2A (acquired 23rd February 2017) (Background: Sentinel 2B acquired 27th February 2021) and (b) 1962-2009 mapped from ARGON KH5 (acquired 16th May 1962), Landsat 1 MMS (acquired 27th February 1974) and Landsat 5 TM acquired (10th -12th February 1991) and from MODIS MOA (acquired 1st November – 28th February 2009) – Modis MOA (Scambos et al., 2007) (Background: MODIS MOA). (c) The floating portion of Scott Glacier in June 2022, highlighting the iceberg that calved from the western front in April 2022 and the rifting across the eastern portion of the front towards Chugunov Island (Background: Sentinel 1A acquired 6th June 2022).

**Figure 5**

- *The caption talks about the “Shackleton Roscoe Glacier”. I thought it was just the Roscoe Glacier?*

We were refereeing to the shear margin between the two. We have changed the caption to say the shear margin between the Shackleton Ice Shelf and Roscoe Glacier and have marked the shear margin location in figure 5 for clarification. See below

- On line 177 you talk about the margin between the Roscoe Glacier and the Shackleton Ice Shelf. Can you mark this margin on the figure?

This has been marked on figure 5 and added to the caption. See below

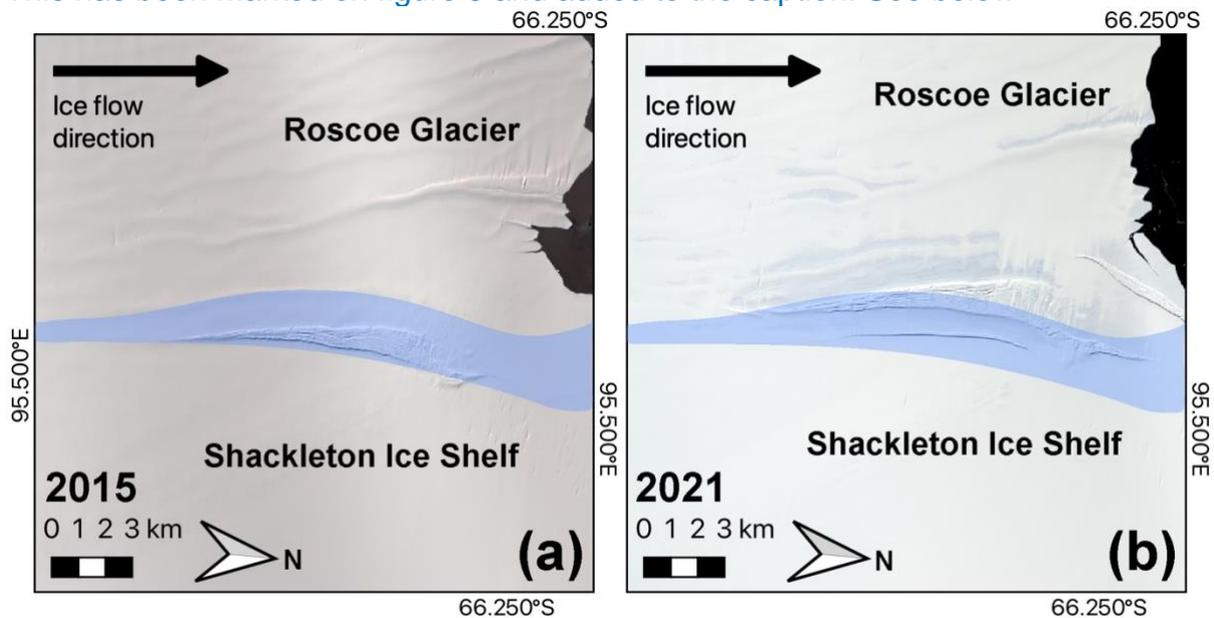


Figure 5: Rift opening in the vicinity of the shear margin between the Shackleton Ice Shelf and Roscoe Glacier (location marked in blue) between (a) 2015 (Background: Landsat 8 OLI acquired 14th March 2015 and (b) 2021 (Sentinel 2B acquired 13th February 2021).

*Figure 6*

- Add year of data collection to each panel

Have added the year to each panel, see below

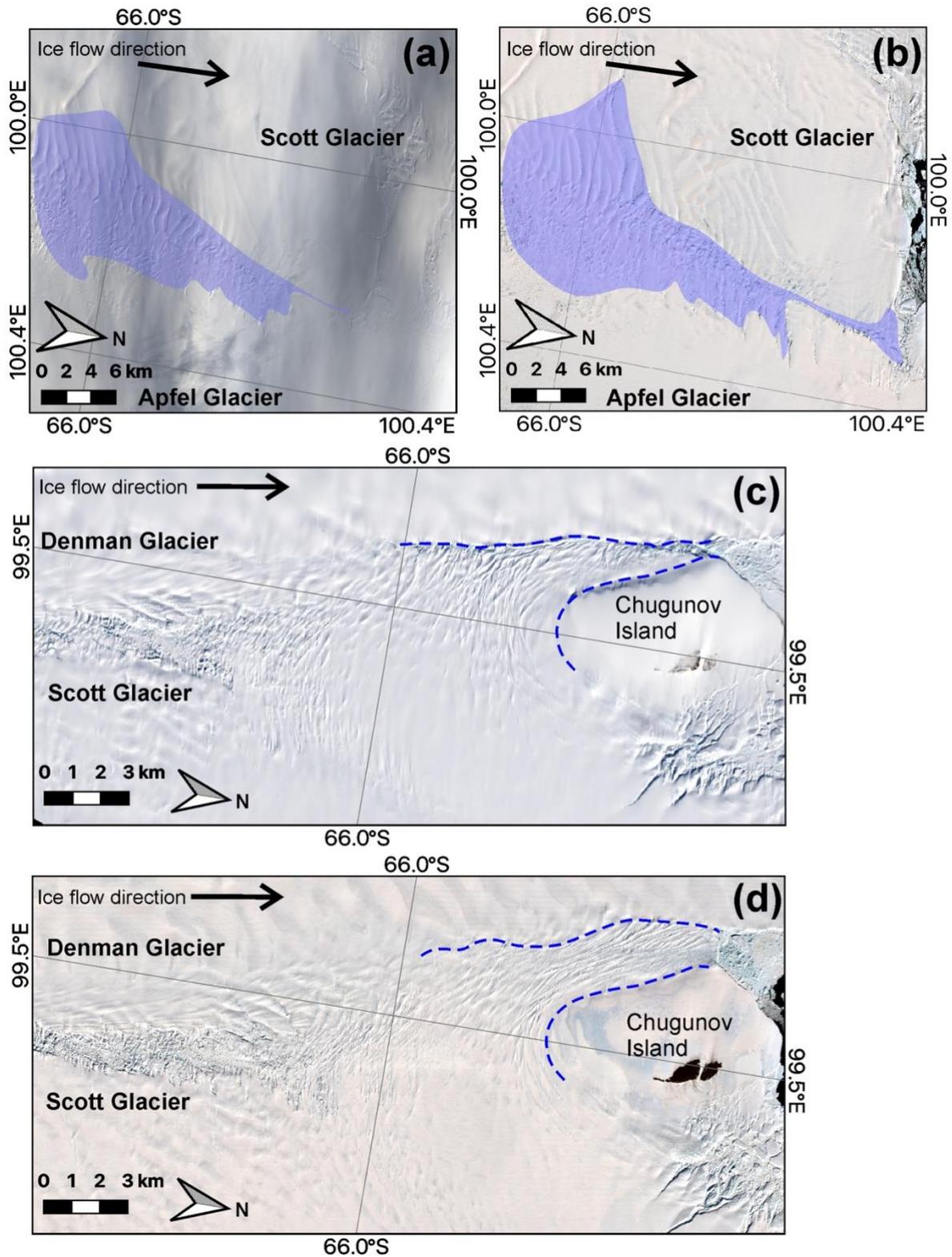


Figure 6: (a) The 2015 extent of the Scott-Apfel Glacier shear margin highlighted in blue (Background Landsat 8 OLI acquired 25th March). (b) The 2021 extent of the Scott-Apfel Glacier shear margin highlighted in blue (Background: Sentinel 2B 13th February 2021). (c) Scott-Denman Glacier shear margin in 2015, the dashed blue line highlights the position and shape of the margin. (Background: Landsat 8 OLI acquired February 2015). (d) The Scott-Denman Glacier shear margin in 2021, the

dashed blue line highlights the widening of the shear margin into the Denman Glacier (Background: Sentinel 2B acquired 27th February 2021).

Figure 7

- Radar name text is on the wrong side. Move all radar names to the left side of the transects in panel a as you are looking at the transects from the sea, not from inland. Have moved to radar name to the left side of the transects, see below
- The radar bed pick key needs a metric (m a.s.l.?)  
Have added m a.s.l. to the key, see below
- Re-title the radar transect names on the right hand column to match those on the map.  
Have re-titled the transect names to match the map, see below
- I'd argue that the power colour bar down each radargram is unnecessary.  
Have changed to a single colour bar top of the figure, see below

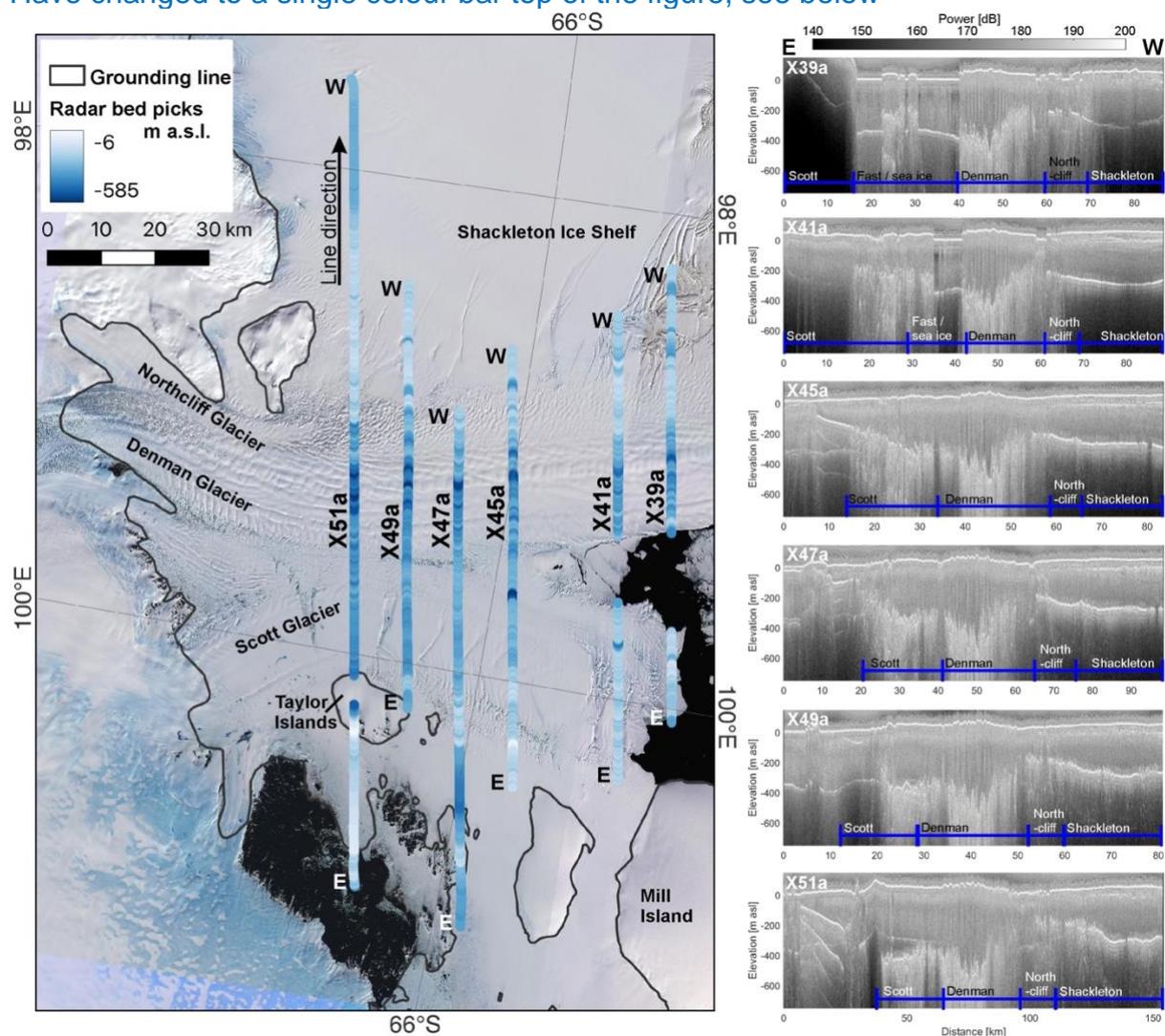


Figure 7: (a) The location and ice base below sea level of 6 ICECAP radar lines acquired in December 2016 (Background Sentinel 2A acquired 23rd February and 1st March 2017). (b) Annotated ICECAP radar lines (position and east-west line direction shown in a).

Figure 8

• Label glaciers again here (and in Figures 9 and 11). You're used to looking at this area so it's clear to you what's what, but most readers won't be. Have labelled all of the glaciers on Figures 8, 9, and 11, see below

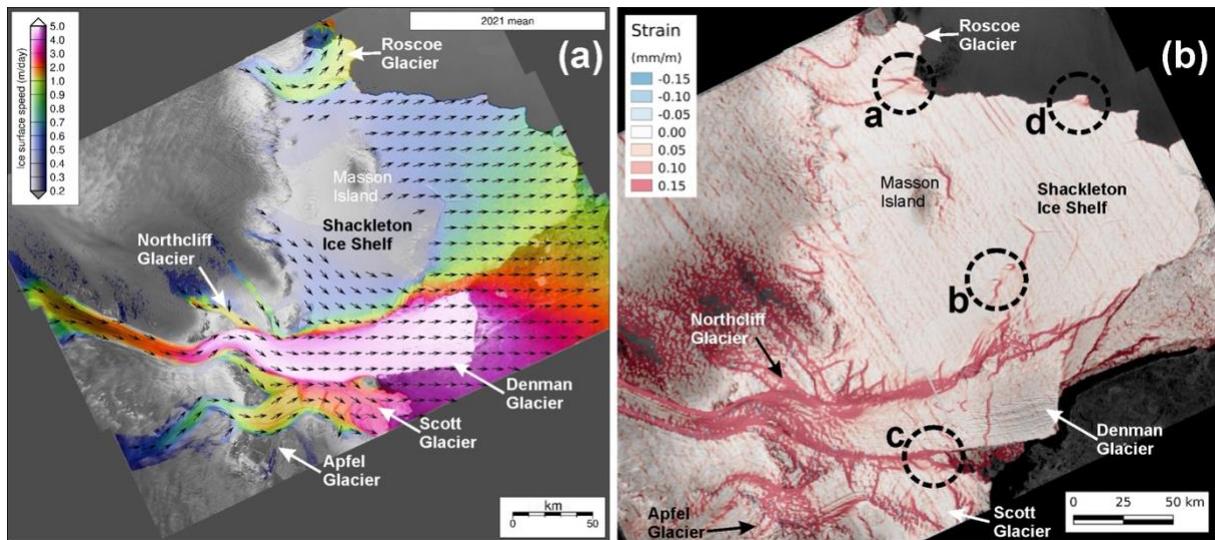


Figure 8: (a) Mean speed for 2022 with velocity arrows. (b) Magnitude of the principal strain rate of Shackleton system derived from Sentinel-1 derived mean velocity data over the period of observation. N.B. The feature down flow of pinning point c on the Denman Glacier tongue is an artefact, we see no evidence of rifting in the remote sensing data in this region (e.g., Fig. 2b, 7a).

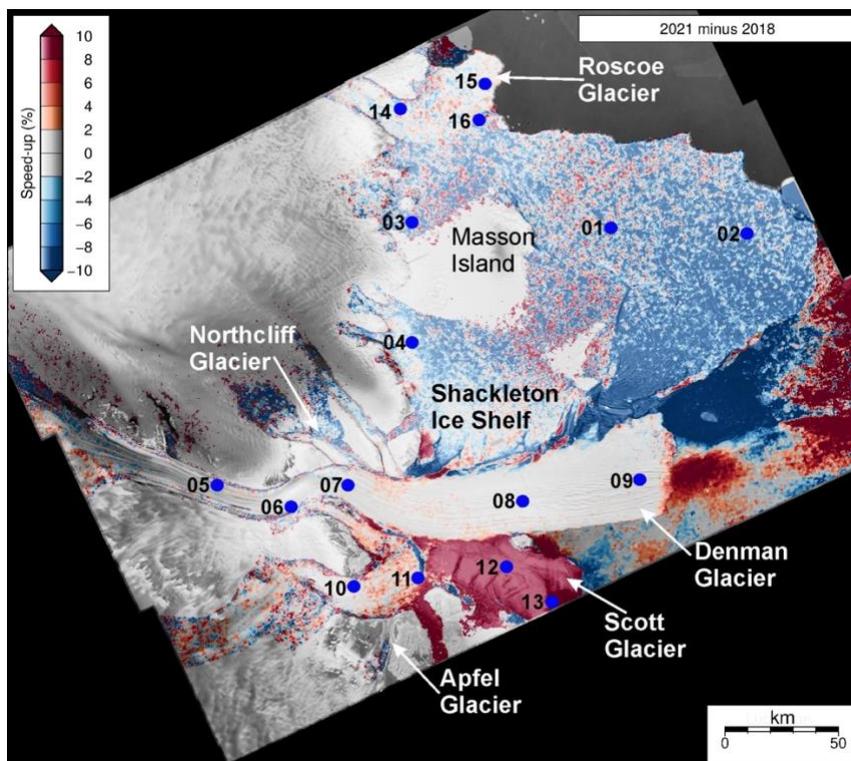


Figure 9: Percentage difference in mean speed between 2021 and 2018, scaled between +/- 10%, with point locations illustrating the ice speed timeseries in Figure 11.

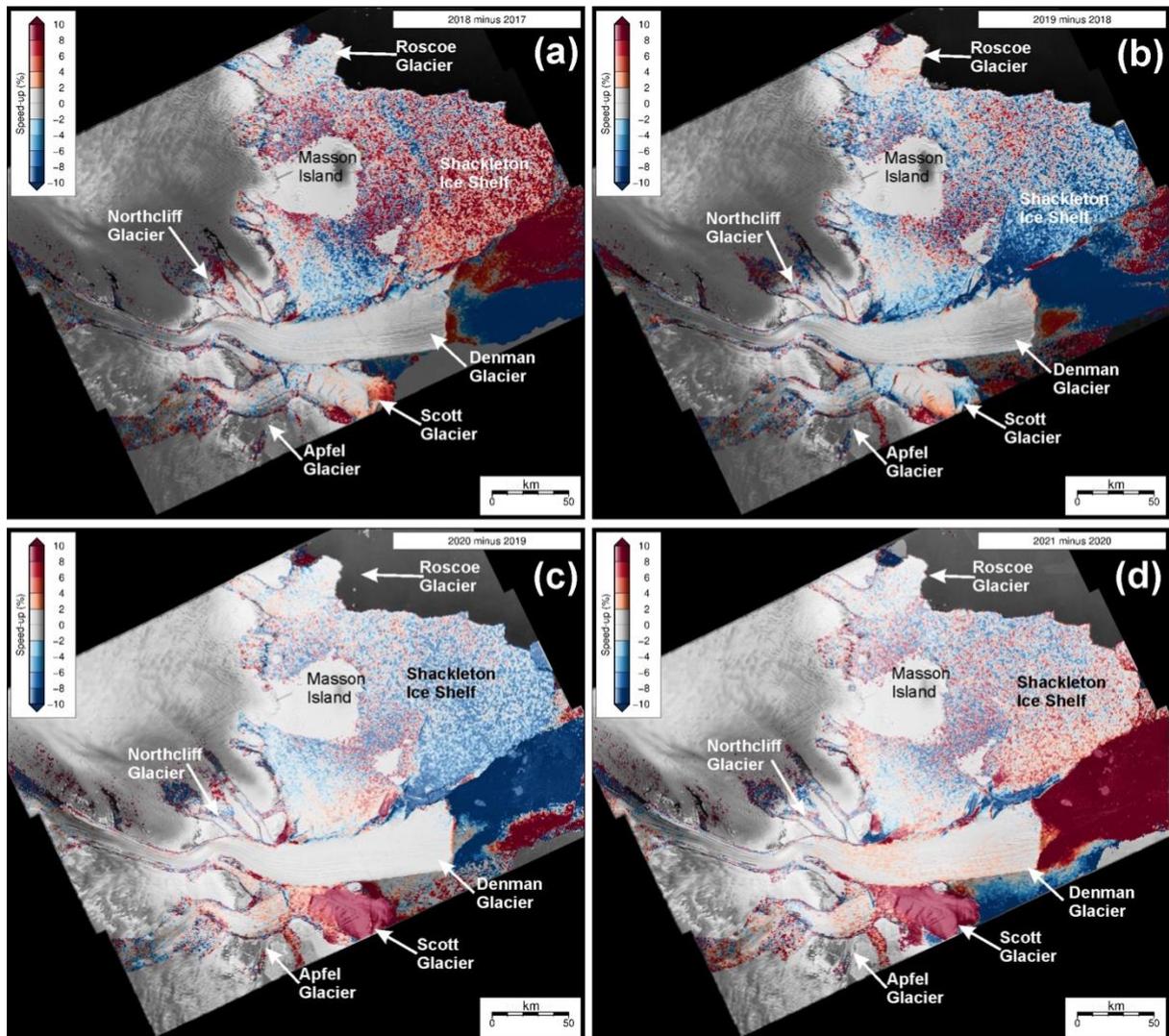


Figure 10: Percentage difference in mean speed between (a) 2018-17, (b) 2019-18, (c) 2020-19 and (d) 2021-20 scaled between  $\pm 10\%$ .

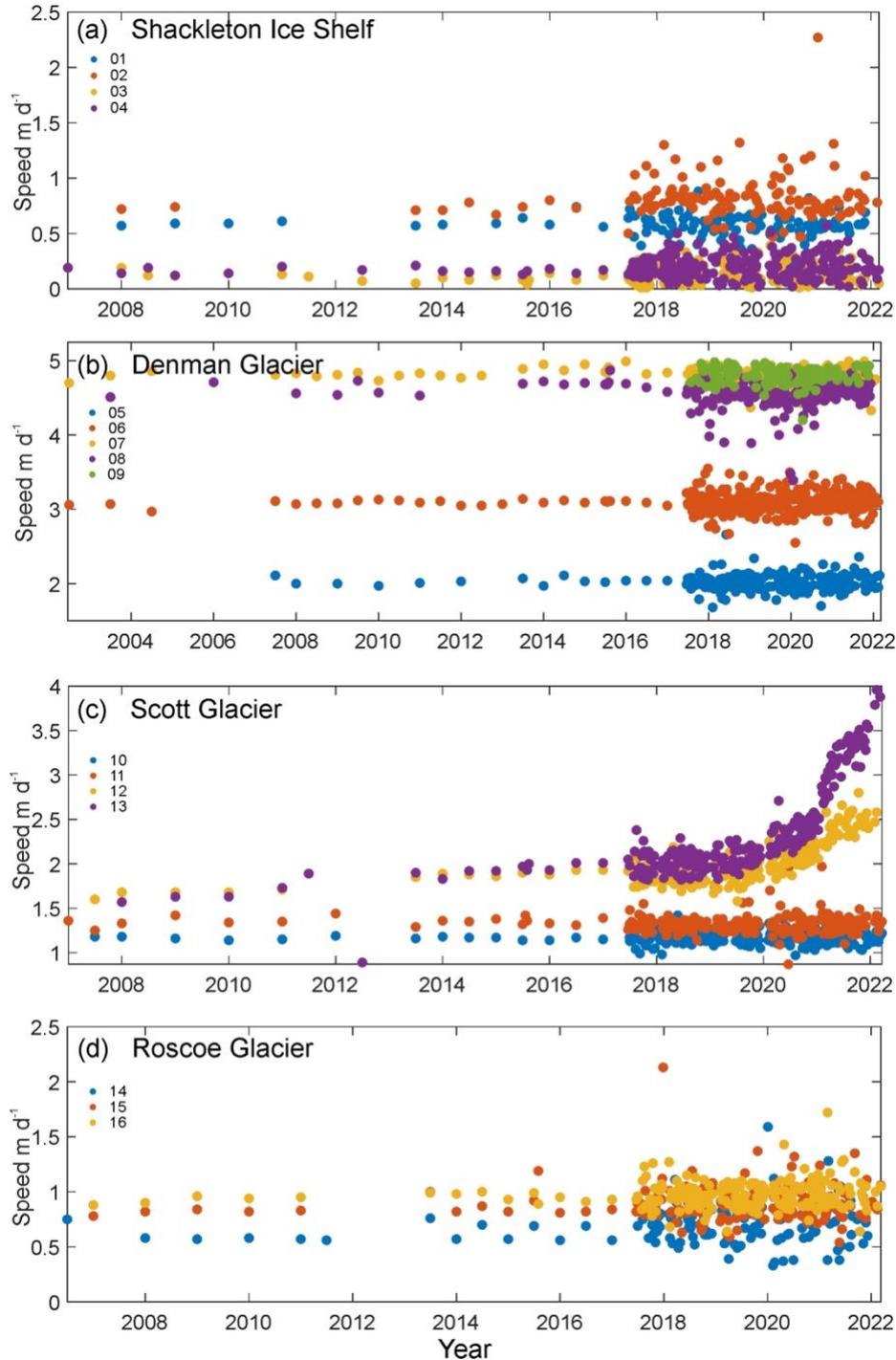


Figure 11: Time series of speed at point locations (shown in Figure 10a) across the Denman-Scott-Shackleton system derived from Sentinel 1 between 2017 and 2021 (uncertainties in velocity magnitude are around 0.2 m day<sup>-1</sup> following (Benn et al., 2019)) and extended back to 2002 using Measures and ITS\_LIVE where available (Rignot et al., 2017).

*Additional, minor comments:*

*Title: Maybe Glaciological history is a better term than setting, which doesn't really mean much.*

We agree that history is more meaningful than setting and have implemented the change, the title now reads

Line 1: Glaciological history and structural evolution of the Shackleton Ice Shelf System, East Antarctica, over the past 60 years

*Line 28: Be more specific. From what speed to what speed?*

The increase is reported at a 15% increase, however we have altered the abstract to better represent our key findings in response to comments by Referee #1 and the sentence has been removed from the abstract.

*Line 30: How do you know acceleration in ice flow and calving are linked?*

We don't know that that the increase in ice flow speed and calving are linked, only that they occur at the same time. We have adjusted the text to reflect this, and the sentence now reads

Line 29-31: Over the period 2017-2022 we observe a significant increase in ice flow speed (up to 50%) on the floating part of Scott Glacier, coincident with small scale calving and rift propagation close to the ice front.

*Line 33: Presumably sediment filled trough rather than just bedrock.*

We agree that it is likely that the trough is sediment filled and have adjusted the text to reflect this, the sentence now reads

Line 33: Given the potential vulnerability of the system to accelerating retreat into the overdeepened, potentially sediment filled bedrock trough, an improved understanding of the glaciological, oceanographic, and geological conditions in the Shackleton system are required to improve the certainty of numerical model predictions and we identify a number of priorities for future research.

*Line 48: This paragraph jumps around. Stick with basin introductions first then move onto the floating components. A more detailed site overview is needed too – to include glacier lengths, thicknesses etc (see points above).*

We agree that the paragraph structure was confusing and lacked basic details. We have added basic basin details (see below) and have fully addressed this comment in response to main comment point 2, please see the above response to point 2 for more detail.

Line 50-69: Ice thicknesses across the grounded portion of the system range from ~ 400 m inland of Shackleton Ice Shelf to > 4000 m at the Denman Glacier (Morlighem et al., 2020). Bed elevations are also wide ranging with the main outlet glaciers grounded well below sea level and experiencing retrograde slopes (Brancato et al., 2020; Morlighem et al., 2020). Close to the grounding line ice thicknesses range from 300 m to 1400 m, thinning toward the ice front where ice thickness is in the range of 180 – 250 m with the exception of the front of the Denman Glacier tongue at

~ 450 m thick (Morlighem et al., 2020). Ice velocity data from the region are sparse before the late 2000s, but recent work identified an increase in ice velocity of the Denman Glacier of ~ 16 % since the 1970s (Rignot et al., 2019), with an increase of  $11 \pm 5$  % just upstream of the Denman Glacier grounding line between 1972-74 and 1989 and a more recent rate of acceleration of  $3 \pm 2$  % between 1989 and 2007-08 (Miles et al., 2021, their Fig. 3c). Analysis of Envisat data indicated that the Denman Glacier was thinning by  $0.4 \text{ m year}^{-1}$  upstream of its grounding line between 2002 and 2010 (Flament and Rémy, 2012), and a  $5.4 \pm 0.3 \text{ km}$  grounding line retreat was detected between 1996 and 2017–2018 (Brancato et al., 2020).

*Line 56: What does the lack of an embayment mean in terms of ‘major dynamic change’? I fail to see the relevance.*

We have removed this statement from the restructured introduction.

*Line 57: Refer to figure 1*

We have now referenced figure 1 and the sentence reads

Line 69-71: Beyond the Denman Glacier grounding zone, there has been much less observation but, rest of the Shackleton system has so far shown few signs of major dynamic change, with its flow restrained by islands, ice rises, and ice rumples (Stephenson et al., 1989; Young, 1989) (Fig.1).

*Line 62: You’ve just said the data is sparse, so how reliable is this information? Can you note any error margins?*

We have added error margins where they are available in the articles we have referenced. The sentence now reads

Line 54-58: Ice velocity data from the region are sparse before the late 2000s, but recent work identified an increase in ice velocity of the Denman Glacier of ~ 16 % since the 1970s (Rignot et al., 2019), with an increase of  $11 \pm 5$  % just upstream of the Denman Glacier grounding line between 1972-74 and 1989 and a more recent rate of acceleration of  $3 \pm 2$  % between 1989 and 2007-08 (Miles et al., 2021, their Fig. 3c).

*Line 71: I presume you mean average basal melt rates rather than total melt rates.*

Yes, we do mean average basal melt rates, we have changed the text accordingly and the sentence now reads

Line 67-69: Satellite derived basal melt rates between 2010 and 2018 revealed high but localised average basal melt rates of  $> 50 \text{ m year}^{-1}$  close to the Denman grounding line (Liang et al., 2021), on par with basal melt rates in the Bellingshausen and Amundsen Sea (Adusumilli et al., 2020).

*Line 73. Introduce all acronyms.* The information about the Sabrina Coast doesn’t seem to have much relevance to your work but I could be reading this incorrectly.

We have changed this paragraph in response to comment from Referee #1. We have ensured all acronyms have been introduced and removed references to the Sabrina Coast. The paragraph now reads

Line 76-83: The high basal melt rates close to the grounding line in this region of Antarctica have been linked to a warming of up to 0.5 °C over the last 40 years that occurred in the open ocean off East Antarctica, concurrent with an even more pronounced warming of 0.8–2 °C observed over the continental slope (Herraiz-Borreguero and Naveira Garabato, 2022). This Circumpolar Deep Water (CDW) warming is linked to a poleward shift of the Antarctic Circumpolar Current's southern extent onto the Indian Ocean sector of the East Antarctic continental slope, in which the Shackleton Ice Shelf is located. The continental slope warming appeared strongest near ice shelves that are thinning or have retreating grounding lines such as the Denman Glacier (Herraiz-Borreguero and Naveira Garabato, 2022).

*Line 74: But how likely is this given what you say in the next sentence? Probably best not to jump to possibilities here.*

The sentence has been removed.

*Line 79: I think you mean grounded.*

Yes, this was a typo, we do mean grounded and have changed the word in the text.

Line 87: You don't mention the multi-decadal timeframe you talk about in the abstract.

This was an oversight; we have amended to text to reflect this, and the sentence now reads

Line 94-95: Here we add to the previously reported dynamic changes in the Denman Glacier over the 60-year period of observation and place them into the wider regional context of the Shackleton system.

*Line 92: Just talk about the Shackleton system rather than the whole coastal area.*

We have made the change and the sentence now reads

Line 102-103: Surface structures and features of the Shackleton system were mapped from satellite imagery using standard GIS techniques (following Glasser et al. (2009)).

*Line 83: Can you briefly state why you chose every 6 months, presumably you have data from February and July/August then? Is that just because of daylight? March to September might allow you to capture more of the seasonal changes? Note that I'm not asking you to change your data analysis period! Just note exactly which months you studied and why you made that call.*

It was a compromise between capturing as much of the potential seasonal signal as possible while still having enough cloud free optical images to cover the system once

a year. We have added a sentence to the methods to explain this. The sentence reads

Line 105-108: We used available optical and SAR imagery from February and SAR imagery from August of each year to allow us to capture any seasonal variation while maximising the number of cloud-free optical images available

*Line 94: The datasets need referenced, or you at least need to provide reference to a data availability section of the paper.*

We have provided links to all of the datasets used in the data availability section of the paper. The section reads

Line 447-456: Data availability

All satellite imagery used in this work are freely available as follows; Landsat 8 OLI, 5 TM and 1 (all downloaded from <https://earthexplorer.usgs.gov/>), MODIS Mosaic of Antarctica 2008-2009 (downloaded from <https://nsidc.org/data/nsidc3350593/versions/2>), Sentinel 2 A and B (all downloaded from <https://scihub.copernicus.eu/dhus/#/home>) Sentinel 1A and B GRD (all downloaded from <https://scihub.copernicus.eu/dhus/#/home>) and ARGON KH-5 (downloaded from <https://earthexplorer.usgs.gov/>). BedMachine (v2) data is freely available (<https://nsidc.org/data/nsidc-0756/versions/2>). The radar-based ice bottom elevation data and radargrams presented here will be published to the Australian Antarctic Data Centre (<https://data.aad.gov.au/>) upon publication.

*Line 110: Reference required for Gamma software*

There isn't a reference as such, but we have added to website, the sentence now reads

Line 122- 124: Using the standard Gamma software (<https://www.gamma-rs.ch/software>) and following commonly adopted methods, feature tracking uses cross-correlation to find the displacement of surface features between pairs of images, which are then converted to velocities using the time delay between those images (Luckman et al., 2007).

*Line 113: How short? Can you give a range?*

The original statement was intended to explain that shorter delays lead to better coherence and where delays are sufficiently short (and no melt etc.) the surface features tracking uses include speckle. While there is not a simple answer to this, we have changed the following sentence to include the possible repeat times for clarification, the sentence now reads

Line 127-128: We applied feature tracking to all image pairs of 6 and 12-day repeat-pass period (about 60 per year) and selected the best single velocity map

*Line 114: The cold temperatures is an assumption. Delete this.*

Happy to delete, the sentence now reads

Line 125-126: Where the time-delay between images is sufficiently short, and surface change is minimized, trackable surface features include fine-scale coherent phase patterns (speckle) and the quality of the derived velocity map is maximized.

*Line 115: Can you note how many image pairs you used to show off the rigour of your work?*

We used roughly 60 images per year and have added this to the text, the sentence now reads

Line 127-128: We applied feature tracking to all image pairs of 6 and 12-day repeat-pass period (about 60 per year) and selected the best single velocity map.

Line 125 (and the rest of the paragraph): More detail required. What frequency did the radar operate at? How was the data topographically corrected? What velocity did you use? Did you apply a firm correction?

We have added the required detail to the section, please see the response to point 3 above.

No firm correction was needed for the qualitative analysis in the present study. The data providers prefer releasing data without a firm correction so that data compilers (e.g. Bedmap, Bedmachine) may apply a consistent approach.

*Line 135: Do you mean no obvious change in the annual rate of advance?*

Yes, we do mean the annual rate of advance, we have clarified this in the text and the sentence now reads

Line 154-155: Over the same time period, the Shackleton Ice Shelf's central front advanced a total of 18 km with no obvious change in the annual rate of advance (Fig. 2a).

*Line 137: Which front are you talking about?*

We are referring to the front of the Shackleton Ice Shelf itself, have clarified this in the text and the sentence now reads

Line 157-158: Between 2015 and 2022, the front of the Shackleton Ice Shelf then advanced steadily by  $\sim 0.3 \text{ km year}^{-1}$  while the Denman Glacier's ice front advanced at a rate of  $1.8 \text{ km year}^{-1}$  over the same time frame, with a uniform pattern of advance and no seasonal variability in advance rate observed (Fig. 2b).

*Line 139: The lack of seasonal change is interesting is it not? So something you should talk about in your discussion?*

We agree that this is interesting, we think there are no seasonal changes in ice flow speed because seasonal forcing observed elsewhere in Antarctica and in Greenland, such as seasonal changes in surface meltwater variability and seasonal sea ice

break up reducing back stress, are currently insufficient to have an observable forcing effect on the Shackleton system. We have added an explanation of this to section 4.3 of the discussion (detailed in response to point 9 above). The section now reads

Line 351-360: The ice flow speed of the Denman-Northcliff Glacier has been constantly  $\sim 5$  m day<sup>-1</sup> close to the ice front over the period 2015-2022, with a uniform flow direction and no observable seasonal variability in flow speed (Fig. 2b, 8a, 11b). While efficient meltwater surface-to-bed connections via moulins and fractures are common in the Greenland Ice Sheet and seasonal changes in surface meltwater variability have been observed to cause seasonal changes in ice flow speeds (Hoffman et al., 2018; Sundal et al., 2011), there is currently very little evidence for coupling between the surface and basal hydrological systems in Antarctica (Bell et al., 2018). However, season variations in ice flow speed have been observed on an outlet glacier in East Antarctica, coincident with seasonal sea ice break up reducing back stress on the system and the onset of seasonal melt thought to weaken the shear margins (Liang et al., 2019). Our results suggest that seasonal variation in sea ice extent or surface melting are currently insufficient to have an observable forcing effect on the Shackleton system.

*Line 145: How do you know it's the calving that's causing the retreat and not faster ice flow or melting?*

We don't know that melting is not contributing but we have no observations of melting here. We do see some indication of small-scale calving events in the form of icebergs adjacent to the ice front and have changed the sentence to report this rather than suggest causation. The sentence now reads

Line 165-166: Since 2020, small scale calving has been occurring on the side of the Scott Glacier adjacent to Mill Island, where the ice front position now lies  $\sim 5$  km inland of the 2015 front (Fig. 3b-d).

*Line 171: How do you define the grounding line?*

The grounding line we use is the same as in the figures, defined by MEaSURES and referenced to Rignot et al., 2017. We have included this in the text and the sentence now reads

Line 198-199: The rifts initiates approximately 20 km down glacier of the grounding line (as defined by MEaSURES (Rignot et al., 2017)) and widen to  $\sim 2.5$  km as they flow around the Taylor Islands.

*Line 179: What happened prior to this? Is there a reason why you don't explore data prior to 2015 here?*

We do describe earlier rift evolution in the following sentence, but we only have sufficient temporal resolution to measure the annual rates of change presented here from 2015 onwards.

Line 183: Why don't you talk about any features on the Apfel Glacier?

We did not discuss Apfel Glacier in this section because we do not observe any significant features or change in this region. We have added a sentence to clarify this which reads

Line 203-205: There is no clear margin between Scott Glacier and Apfel Glacier offshore of the Tylor Islands and no observable rifts on Apfel Glacier inland of the Tylor Islands (Fig. 4a).

*Line 186: Reference not needed as it's your observations that show this.*

We have removed the reference and the sentence now reads

Line 232-233: The Scott Glacier floating shear margin that abuts the Denman Glacier is more clearly defined and has been widening into Denman Glacier in the vicinity of Chugunov Island (Fig. 6c-d).

*Line 188: Why is this remarkable? A statement like that needs to be backed up by other references that say this situation is really unusual. I'd use the word notably, or something similar instead.*

We agree and are happy to make the change. The sentence now reads

Line 234-235: Notably, the shear margin appears to bulge progressively into Denman Glacier and is double the width by 2022 as compared with 2015 (Fig 6c-d).

*Line 191: You should say the radar provides a snapshot of information.*

We agree and are happy to make the change, the sentence now reads

Line 208-209: The ICECAP airborne radar lines flown in December 2016 provide a snapshot of information about the thickness and ice structure through the floating ice.

*Line 195: Split is the wrong term. The ice doesn't fracture apart.*

We agree and have changed the text accordingly, the sentence now reads

Line 213-214: The Denman tongue appears to consist of two distinct longitudinal sections with very different ice thicknesses,

*Line 199: What's consistently noisy? Radar returns? The bed?*

We have removed this sentence.

*Line 232: Use precise dates here rather than 'beginning'.*

Happy to make the change, the text now reads

Line 276-277: However, the downstream 30 km of the floating ice tongue show significant acceleration from the January 2020 through to May 2021.

*Line 239: What time span do you analyse here?* – Emailed Adrian

The magnitude of principle strain rate is derived from the mean velocity maps from 2017-2020, we have added this to the text and the sentence now reads

Line 244-245: The magnitude of the principal strain rate, derived from the mean velocity maps (2017-2020), highlights the shear margins of the Denman Glacier and Roscoe Glacier with the Shackleton Ice Shelf and the shear margins of the Scott Glacier (Fig. 8b), as well as four pinning points across the system (Fig. 8b).

*Line 241: I think you mean to refer to figure 11.*

Yes, we do mean Figure 11 and have corrected the reference.

*Line 247: What do you mean by that? Longer-term change in what? Glacial output?*

This sentence has been removed in the restructuring of the discussion in response to the main points above.

*Line 274: This reads like a literature review. How does it relate to your findings? You never talk about mélange.*

The detail was included in response to a previous review request. We have shortened the section and discussed the relevance to our findings, the paragraph now reads

Line 311-326: The lack of significant rift propagation in rift system R1 on the main body of Shackleton Ice Shelf appears directly related to the Masson Island suture zone (Fig 2a). Indeed, there is growing recognition that the softer marine ice present in suture zones inhibits the growth of large-scale fractures, acting to stabilise ice-shelves by reducing local stress intensities (Kulesa et al., 2014; Larour et al., 2021; McGrath et al., 2014). While current observations suggest suture zones promote stability by halting rift propagation, a strong relationship between the thickness of ice mélange found in suture zones, and the opening rate of the rifts has been observed, indicating that ice mélange thinning rather than ice shelf thinning can promote rift propagation (Larour et al., 2021). The increased sea water content and warmer temperature of the ice mélange suggests it may be more vulnerable to thinning due to future surface and basal melting than the surrounding meteoric ice, potentially affecting rates of rift opening and propagation (Kulesa et al., 2014, 2019; McGrath et al., 2014). Rift system R2 has undergone more significant change over the period of observation, although the rift tip does not appear to have reached the Masson Island suture zone (Fig. 2a) as yet and may experience a similar behaviour to that of R1 when it does. With prominent suture zones and pinning points as likely agents of stability (Kulesa et al., 2014, 2019), increased ice shelf thinning could lead to a significant calving event due to coincident suture zone thinning and further rift propagation, with unpinning of the ice shelf on the side of the Shackleton Ice Shelf adjacent to Roscoe Glacier ('d' in Fig. 8b). The relatively slow grounded ice flow

speeds onshore of the Shackleton Ice shelf suggests such a calving event is unlikely to initiate an increase in ice flow into the ocean, indeed it is considered passive in terms of ice buttressing (Fürst et al., 2016).

*Line 275: Of what ice melange? At your study site?*

We are referring to the ice melange found in suture zones and have clarified this in the text, the sentence now reads

Line 314-316: While current observations suggest suture zones promote stability by halting rift propagation, a strong relationship between the thickness of ice mélangé found in suture zones, and the opening rate of the rifts has been observed, indicating that ice mélangé thinning rather than ice shelf thinning can promote rift propagation (Larour et al., 2021).

*Line 278 (the paragraph): Contains lots of results again, but you need to discuss what the results mean for your study site and out knowledge of antarctica and processes as a whole.*

This section has been re-written in response to the main points. Please see the detailed response to main point 9 for details.

*Line 294: What do you mean by 'connection'?*

This section has been re-written in response to the main points. The sentence now reads

Line 372-374: The observed changes in ice front position of Scott Glacier are coincident with a doubling of ice flow speed at the ice front, from 2 m day<sup>-1</sup> in January 2020 to 4 m day<sup>-1</sup> in January 2022 (Fig. 11c). The increase in ice flow speed extends from the ice front to rift S1 but is not observable inland of this feature.

*Line 305: How do your results underpin this hypothesis?*

This section has been rewritten in response to the main points above. Please see the response to main point 10 for more details.

*Line 320: It's unclear exactly what data you need more of. Do you need better bed topography data in the region? Or do you want better ocean temperature data? How will a knowledge of local geology help? This statement is rather generic and therefore unhelpful.*

We have rewritten the section to provide specific suggestions for future priorities, the section now reads

Line 431-437: The potential vulnerability of the Shackleton system to increasing atmospheric and ocean forcing, the magnitude of potential sea level rise of the Denman Glacier alone (~ 1.5 m) (Morlighem et al., 2020) and the potential link to the Aurora Subglacial Basin (through the Knox Basin) make this region of East

Antarctica one of significant importance in improving predictions of sea level rise. Critical to assessing the timing and magnitude of sea level rise contributions are improvements in the measurement of ice cavity bathymetry, subglacial conditions, and the evolution of surface melt water systems, as well as targeted collection of field data to allow better incorporation of features such as suture zones, pinning points and brine infiltration into numerical models of ice shelves.