nature portfolio

Peer Review File

Ross Gyre variability modulates oceanic heat supply toward the West Antarctic continental shelf

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

9th Oct 23

Dear Dr Prend,

Please accept our apologies for the delay in obtaining reports on your manuscript titled "Ross Gyre variability modulates oceanic heat supply to the West Antarctic continental shelf". Your manuscript has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

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

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

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

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

Best regards,

Clare Davis, PhD
Senior Editor
Communications Earth & Environment

Jennifer Veitch, PhD
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Prend et al., use B-SOSE and particle experiments to examine how the Ross Gyre connect the open ocean to regions close to the continental shelves of Antarctica.

The study is very interesting and the article is well-written. It was a pleasure to read and, most importantly, this work advances our understanding of the Southern Ocean.

I have some major comments around: a) the strength (and evidence for) some of your conclusions, b) including errors, and c) a bit more context. I also have a number of minor comments mostly regarding the text structure. By addressing these comments, I think that the clarity and significance of your findings will be improved.

Major Comments:

(a) Connectivity between the open ocean and shelf seas: I agree with the authors that the 'offshore heat reservoir' is important to understand. However, the Antarctic Slope Current Front still provides a barrier to exchange between the open ocean and shelf seas. So, if that barrier is strong it doesn't really matter what is happening offshore of the slope front. At the moment, I am not entirely convinced by some of your statements relating this study to 'transfer of oceanic heat from the open ocean to the ice shelf cavities'. But statements like 'Gyre expansion favors the movement of particles toward the Amundsen Sea' are clear to see. I think that this issue can be addressed by shifting the focus of your conclusions somewhat and/or providing further evidence of the link between the open ocean and the shelf seas. Specific suggestions with how to address this comment…
o Can you provide some additional evidence and/or discussion that the water of this offshore reservoir is crossing the slope front. This might be as simple as linking to work that shows cross-shelf/slope exchange and adding in a sentence or two about the fact the slope current front is a barrier, but it is overcome.
o Can you add the position of the Antarctic Slope Current Front to all of your map panels in your figures.
o L155: 'The meridional heat transport through this transect…' This transect is far from the slope, can you do the same calculation for a region at the slope for both the weak and strong cases? This would provide convincing evidence of the connection between the open ocean and shelf seas.
o In figure three, the meridional transect (black dashed line) is far from the edge of the gyre (green

line). Why have you chosen to look there, as they seem far away and disconnected. I'd either move the transect close to the gyre edge, or explain why you have put it there (which I may have missed).

(b) Errors and physical meaning of strong/weak years:
o For the gyre strength, can you make some estimate of the error.
♣ For a sensible (i.e. physically sensible) error, what about considering the time scale is takes for some heat anomaly to travel from the offshore reservoir to the slope edge. Say that is about a month(?), what is the monthly variability in gyre strength? Once you do have an error, could you add it to the plot in 2a and discuss what that means for your conclusions in the paper? You allude to this with this sentence here: 'We note that gyre anomalies cannot be instantaneously communicated to the shelf.'
♣ What is you choose a different Sverdrup contour?
o I'd recommend adding errors to your other important properties, like heat transport.

(c) Looking forward and broader context: There has been some dramatic changes in the Southern Ocean recently. Can you add a few sentences to discuss how your work relates to possible longer-term changes and/or recent changes in sea ice?
o L250: 'gyre expansion is due largely to negative sea ice concentration anomalies in the region (Extended Data Fig. 3)rather than variability in the wind stress.' Cool, can you add some sentences along the lines of what the recent declines in sea ice may mean for the results of this study.
o L213 onwards: Could you spend a bit more time explaining what the limitations of the 6-year period of analysis are, specifically possible decadal trends.
o If it takes several years to get from one end of the gyre to the slope, what does that mean for the possible changes in heat transport onto the shelf?

Figure Comments:

Overall, the figures are clear and get the message across. A few design suggestions below to help improve clarity.

General,
- do the symbols in the figure captions need to be defined in each figure caption? Or replace the symbols with the name itself.
- The colour of the land, PF, and Sbdy change between figures. Could you keep them consistent?
- The pink and orange of the PF and Sbdy is quite hard to see in some places.
- Define 'Sbdy' and 'PF' acronyms. Even better, have their full names in the text.

Figure 2:
- Can you add annotations for weak and strong gyre to the relevant place in 2a. I'd also add 'weak' and 'strong' next to the year label.
- Add the green boundaries from Fig. 3 to Fig 2.

Figure 3:
- I think it would be better to show some sort of temperature anomaly here, as the absolute temperature over 2013 to 2018 could be influenced by a trend.
- I'd make the purple and yellow stars bigger – the purple one is quite hard to find

Extended Data 3:
- Explain what a negative value means (i.e. more sea in 2014) and what that means for gyre strength/shape.

Heat Transport plots:
- State in the caption what the transport is relative to and what the sign means.

Particle Trajectory plots:
- Some small arrows and/or annotations to show the difference between the strong and weak years. These will aid the reader in following your conclusions. You may be limited on space, but a schematic could be useful to add to the figure set.

Minor Comments:

Abstract: A few places where there is jargon. As this is being submitted to the nature journal family, it might be better to replace these words with those that are more accessible to general readers. For example, 'ocean surface stress curl'.

L19-21: I'd switch the order of these sentences to something like '…by the end of the century. So, determining its drivers is crucial to improve future sea-level and climate projections. However, ice shelf melt exhibits significant spatiotemporal variability.'

L66: can you add this '1/6◦ nominal resolution' in km as well?

L67: 'Earlier iterations of this model have been used to investigate Ross Gyre transport33, 38 and its relationship to the thermohaline structure of the region.' Ok – and is the implication that B-SOSE is a reasonable representation of the Ross Gyre, if so can you state that please?

L69-71: Maybe this is too technical for the main bit of text here. I reckon that this statement would be better suited to the methods, and a statement like my comment above to replace it.

L75: 'barotropic streamfunction' is a bit of jargon. And, its significance is not defined in the Methods. I'd suggest defining it when it first comes up in the methods (e.g. 'Here, we define the position of the Ross Gyre using…') around L236. And adding something similar to the main text for further clarity.

L88: a similar comment for 'ocean surface stress' . You have a very clear explanation in the methods (L245-252). Could you add something along the lines of '…ocean surface stress – the force applied to the ocean surface via wind and sea ice - …' in the Methods, as well as the first time ocean surface stress is used in the main text?

L94: At this location 'stronger cyclonic curl' is confusing. I see you explain it in L102-103. I suggest removing this sentence here, and ending the paragraph on the preceding statement re. high correlation.

L98: I was initially a bit confused by 'end-member years', what about 'case studies of contracted and expanded'.

L106: you could add ‘blue shading’ to ‘(Fig. 2c)’ to be really clear.

L112: I understand what you are saying, but perhaps a temperature anomaly would be better to show in Fig. 3a. And, what are you calculating the temperature anomaly (in the other panels) relative to?

L128: Why did you choose to run them backwards? Could you explain a bit more here what that means and why that choice was made? In other words, can you indicate where the particles were released, as well as their origin (which I think is different in this case)?

L139: I’d start the paragraph with a topic sentence for example ‘We used the strong and weak case study years to text the ….’. In general, a few of the paragraphs would benefit from a topic sentence at their start to help the reader along with the story.

L145: ‘…not reflect realistic trajectories.’ Good to state this. Instead, does it reflect a trend? If you feel confident in that, perhaps it would be interesting to add this here, or in your discussion?

L147-152: I am a confused by these statements. Just looking at Fig 4a and b (i.e. the trajectories), it looks like the weak gyre states provides more connection between the shelf and open ocean, because more of the particles cross the thick black line defining the shelf edge. I agree that there are more orange particles further east in the strong case (Fig. 4c), but I do not follow how you have concluded the rest of the sentences. I think that this section needs work to clarify what you mean. Also see my first major comment.

L185: At the moment this statement is a bit strong, given my first major comment.

Conclusions: I have not focused too much on the conclusions for now, as I think this section may change given my comments above. However, I do think that there is some jumbling between: i) what you have done, ii) what others have done, iii) implications, and iv) caveats. I recommend a re-arrange, so that you have a few paragraphs along the lines of: i) what you found, ii) what the implications of your work are, iii) placing that in the context of others, iv) caveats, v) overall conclusions and implications.

Reviewer #2 (Remarks to the Author):

Prend et al use a state-of-the-art data-assimilation model (B-SOSE) to analyse the role of the Ross Gyre in delivering ocean heat toward West Antarctica, where ice shelves are rapidly melting due to warm Southern Ocean waters. I find the manuscript very interesting, especially because much of the focus to date has been on local drivers of ice shelf melting in the Amundsen Sea, while we expect that large scale ocean circulation can play a key role, especially on long time scale. The analysis is appropriate, the manuscript well written and the topic highly relevant to the climate science community and beyond. I have one main comment and few minor comments below.

Main Comment

• Line 179-188: If the particles take years to get from the Ross Gyre to the shelf break of the Amundsen Sea, we could imagine that "interannual signals" of the gyre strength could be dampened, and therefore we might need to think in terms of decadal (or longer) variability. Also, how modelled warming in 2018 on the Amundsen Sea continental shelf can be caused by gyre variability if it takes years to propagate? And related to this, you show along isopycnal warming, suggesting some role of isopycnal mixing. Is there a role for isopycnal heaving? I would add a paragraph to discuss about these points, potentially highlighting some further caveats due to the simulation period (6 years).

Minor Comments

• Extended Data Figure 1. I would mention in the caption what the dotted black box represents.
• Line 97-111: Would it be possible to extract the wind stress curl and compare it between 2014 and 2018. This to understand whether the difference in sea ice is the cause of the difference between the 2 years.
• What bathymetry is used in the model?
• Line 189-202: looking at Figure 4, it seems that the model has a weak undercurrent at the shelf break (or maybe a westward flow in the CDW layer). Is this correct? Maybe it depends on the release location. In case the undercurrent is not captured by the model, would this have implication on your conclusions about the role of the Ross Gyre?

Reviewer #3 (Remarks to the Author):

This is an interesting and highly relevant paper, given the societal importance of understanding the future of the Antarctic Ice Sheet and its vulnerability to ocean heat. The paper shows that the size and strength of the Ross Gyre respond to changes in surface stress over the gyre. Stronger forcing drives expansion of the gyre, which alters the circulation pathways near the Antarctic continental shelf. An expanded gyre means that more water flows east to the Amundsen Sea after the poleward limb of the gyre bifurcates on reaching the continental slope. The authors argue this increases the reservoir of heat offshore of the Amundsen Sea and therefore allows more heat to reach the continental shelf where it can drive enhanced basal melt of ice shelves.

The analysis provides a compelling case that the size and strength of the gyre responds to changes in surface stress and that an expanded gyre results in a more direct pathway from the open ocean to the Amundsen Sea continental shelf. However, a key part of the story seems to be missing: the analysis stops short of showing that these changes alter the reservoir of heat offshore of the Amundsen Sea continental shelf. (The paper does show that the expanded gyre state coincides with warm anomalies at the shelf break and on the continental shelf, but these anomalies are not shown to be related to the mechanism proposed in the paper, as discussed in more detail below.)

To some extent, the paper wants to have it both ways: the authors argue on the one hand that SOSE is not the right tool to look at changes in heat over the continental shelf, as it is missing some key processes that transport heat across the shelf break and across the continental shelf; on the other hand, the title and concluding comments make an explicit connection between variations in the Ross

Gyre and the heat supply to the continental shelf and ice shelves. The language might need some slight adjusting in places to avoid overreach.
If variations in the gyre can be tied more directly to changes in the heat reservoir offshore of the Amundsen Sea, then the paper will be suitable for publication and will make a valuable contribution to the ongoing discussion of processes regulating the delivery of ocean heat to the Antarctic continental shelf.

Specific comments:

The authors show that the main difference between contracted and expanded gyre states is the stress driving the ocean, which in turn depends heavily on sea ice. If the gyre controls heat delivery to the shelf, and the strength of the gyre depends on sea ice cover, this implies that sea ice anomalies in the open ocean modulate heat delivery to the shelf. This might be worth highlighting.

The particle tracking does a good job of illustrating the change in circulation between the contracted (2014) and expanded (2018) gyre states. In particular, it's clear that a larger fraction of particles head east to the Amundsen Sea in the expanded gyre state. But the paper does not provide much evidence to support the overarching conclusion that changes in the Ross Gyre modulate the heat supply to the West Antarctic continental shelf. For example, there is no quantitative analysis of the change in heat content of the off-shelf reservoir and of its dependence on changes in the Ross gyre. A quantitative heat budget for a closed volume offshore of the Amundsen Sea shelf break might be useful; if the proposed mechanism holds up, I guess there should be larger eastward heat flux entering the box through the western boundary, and an increase in the off-shelf heat reservoir. Heat flux across a short transect between 130W and 135W is shown, but this is a long way from the West Antarctic shelf. Calculations of the heat transport across additional sections along the pathway identified by the particle trajectories might be done to show that the stronger/expanded gyre does indeed carry more heat to the Amundsen Sea shelf break.

It's not so clear to me why the 27.9 neutral density surface is used to illustrate changes in CDW. The text suggests this is "the core" of CDW (line 70), but it's not clear what it meant by "core". The CDW (upper and lower) spans a wide depth and density range. Water properties on the 27.9 surface are quite different from slightly denser isopycnals that also lie within the CDW layer (at least in the observations, and presumably in SOSE). The 27.9 surface has a very strong temperature gradient along the isopycnal (as illustrated in Fig 1), because the isopycnal shoals to approach the surface in the Ross Gyre. Based on neutral density sections on WOCE P15 or WOCE S4-Pacific (e.g. http://woceatlas.tamu.edu/images/printed/jpg/S4_gam_right.jpg), this isopycnal sits in the T-min layer in the Ross Gyre, suggesting it outcrops in winter. This is not really CDW anymore – it has had its water properties heavily modified by interaction with the winter atmosphere (i.e. is now Antarctic Surface Water). Where the isopycnal deepens on the edge of the gyre (near 145W on S4), the temperature rapidly increases. I think this explains the large temperature anomalies on this isopycnal around the rim of the gyre when the gyre expands or contracts (Fig. 3). You would get a very different picture if you used a neutral density surface in the CDW layer that did not outcrop in winter, but did access the continental shelf in the Amundsen Sea.

This doesn't mean that 27.9 is a bad choice – the strong isoneutral temperature gradients mean that expansion or contraction of the gyre gives the strongest temperature signal on this isopycnal – but the choice needs to be justified. This justification should make clear whether this isopycnal is chosen to illustrate expansion or contraction, or because it is particularly relevant to the issue of heat transport to the Amundsen Sea. If the latter was true, this would be strong justification for using this density surface, but I can't see how this is the case.

There is also no justification provided for the choice of 130 to 135W, 67S as the place to look at heat transport by the gyre. Is the poleward heat transport by the eastward limb of the gyre sensitive to this choice? In the Abstract, it says "Gyre expansion, linked to stronger ocean surface stress curl, increases poleward CDW volume transport along the gyre's eastern limb and the subsequent heat transport toward the Amundsen Sea and the WAIS." This short section does not span the entire eastern limb of the gyre in either the contracted or expanded states, so I don't believe a comparison of heat transports across the short section is sufficient to support this conclusion.
In the abstract, it says "Strong temperature variability on CDW density surfaces occurs at interannual timescales due to the redistribution of heat between the gyre and continental shelf." I don't believe any evidence is provided in the paper to support this statement, as there is no quantitative analysis of heat content or transport (except across the short control section between 130 and 135W). The strong temperature anomalies around the rim of the gyre do not necessarily imply a redistribution of heat: they could reflect movement of the sharp gradient of temperature along the 27.9 surface near the gyre edge, as noted above. If the argument is that, in the expanded state, cooling around the gyre rim is the result of heat being advected away from the gyre and onto the continental shelf, I think this is unlikely to be correct. (Would the authors argue the reverse is true for the contracted state: that heat advection from the continental shelf to the edge of the gyre explains cooling on the shelf and warming around the rim of the gyre?) Perhaps I am missing the point, but if this is indeed the argument, it requires a quantitative demonstration (and if I am missing the point, the point needs to be clarified).

Figure 3 is a key figure because it is the only one that shows information about temperature anomalies, and so is central to the argument that variations in the gyre modulate heat transport to the Amundsen continental shelf. But I am not sure it really supports the argument very well. The maps in panels (b) and (d) are dominated by the temperature anomalies around the rim of the gyre and on the continental shelf. In contrast, temperature anomalies are weak along the flow path inferred from the particle trajectories. In Fig. 5, it is shown that the increase in heat transport across 130-135W @ 67S is mostly due to stronger velocities, rather than warmer temperatures, so it might not be a surprise that this advective pathway does not show up clearly in a map of temperature anomalies. This is why a direct analysis of changes in heat content near the Amundsen Sea is needed to provide stronger support for the hypothesis.

Panels (c) and (e) also don't support very strongly the argument that advection of heat from offshore drives warming on the shelf. The sections show strong warming in the expanded gyre case at the shelf break, with strongest warming above the 27.9 isopycnal, but weaker warming offshore. If advection along the long pathway from the Ross gyre is the driver of changes in offshore heat content, why is the warming enhanced over the shelf break? Could other mechanisms (e.g. wind-driven changes in the Antarctic Slope Front) drive the strong temperature anomalies over the shelf break and on the continental shelf? I'd encourage the authors to look more carefully at the origin of the temperature anomalies over the shelf break and on the shelf. Can they be unambiguously attributed to advection of heat from the Ross Gyre?

Line 52: "The off-shelf heat availability to the WAIS is, therefore, regulated by interannual variations in the gyre
circulation," But 'off-shelf heat availability' is never shown?

Line 118: “We note that gyre anomalies cannot be instantaneously communicated to the shelf. Still, the time series of CDW temperature in the central gyre and in the Amundsen Sea display opposing trends over the 6-year model run (Fig. 3a). By following a meridional transect offshore from Pine Island and Thwaites glaciers, we also find that temperature anomalies on the Amundsen shelf connect smoothly to offshore anomalies” Fig 3a is not very convincing – there could be other causal factors (e.g. changes in the Antarctic Slope Front), especially as elsewhere it is stated this model is not well-suited to simulating changes in the processes carrying heat onto the continental shelf (so why show a shelf water time series?). As noted above, Fig 3b does not really show a “smooth” connection between on- and offshore – rather a strong maximum at the shelf break, with much weaker anomalies offshore.

Line 154: “along a transect that extends from 130 to 135◦W at 67◦S—capturing the core of the gyre’s eastern limb” does it cross the “core” of the eastern limb in both the contracted and expanded states? (or is heat transport higher in expanded state because more of the gyre occurs in this longitude band?)

Line 203: “We have demonstrated that Ross Gyre variability can modulate the offshore heat reservoir adjacent to the Amundsen Sea at interannual timescales and thus deserves further investigation in the context of WAIS melt”. But there are no plots or analyses of the offshore heat reservoir changes with time?

Line 224: “Furthermore, an expanded gyre implies enhanced melting of the most vulnerable ice shelves in West Antarctica” Up until now, the authors have been suitably cautious, given that SOSE is not believed to capture the processes that may control how much heat crosses the shelf break and ultimately reaches the ice shelf. But here they draw a direct link between the gyre and basal melt, a link not supported by the evidence provided.

Steve Rintoul

The authors would like to sincerely thank the reviewers for their kind, constructive, and helpful comments. It's wonderful to receive reviews with such thought and care put in. We have revised the manuscript in response to the reviewers' comments, which has greatly improved the paper. Following feedback from all reviewers, the manuscript now provides a quantitative assessment of the changes in the offshore heat reservoir adjacent to the Amundsen continental shelf. We show that offshore warming is driven by a zonal heat transport convergence that is consistent with increased supply of CDW from the gyre's eastern limb. Additionally, we have tried to better frame the objectives of our study and connect it to previous work on cross-slope CDW transport. More detailed changes are described below. Note that line numbers refer to where the changes appear in the non-track changes version of the revised manuscript.

REVIEWER 1

We greatly appreciate the time and effort that went into these comments, which are copied in bold below. The following are our point-by-point responses.

Prend et al., use B-SOSE and particle experiments to examine how the Ross Gyre connect the open ocean to regions close to the continental shelves of Antarctica.

The study is very interesting and the article is well-written. It was a pleasure to read and, most importantly, this work advances our understanding of the Southern Ocean.

I have some major comments around: a) the strength (and evidence for) some of your conclusions, b) including errors, and c) a bit more context. I also have a number of minor comments mostly regarding the text structure. By addressing these comments, I think that the clarity and significance of your findings will be improved.

Thanks for your kind and thoughtful feedback, which has strengthened the manuscript significantly! See below for our response to your major comments.

Major Comments:

(a) Connectivity between the open ocean and shelf seas: I agree with the authors that the 'offshore heat reservoir' is important to understand. However, the Antarctic Slope Current Front still provides a barrier to exchange between the open ocean and shelf seas. So, if that barrier is strong it doesn't really matter what is happening offshore of the slope front. At the moment, I am not entirely convinced by some of your statements relating this study to 'transfer of oceanic heat from the open ocean to the ice shelf cavities'. But statements like 'Gyre expansion favors the movement of particles toward the Amundsen Sea' are clear to see. I think that this issue can be addressed by shifting the focus of your conclusions somewhat and/or providing further evidence of the link between the open ocean and the shelf seas. Specific suggestions with how to address this comment…

Thank you for this comment as it is important to clarify the aim of our study. Our intent is to highlight mechanisms of variability to the offshore heat reservoir, since these have largely been ignored in the literature. However, we agree that changes in the offshore reservoir are just one piece of the story in terms of controlling the transport of heat onto the continental shelf. The purpose of our Figure 6 was to try to place the gyre variability within the context of the known variations in cross-shelf exchange (i.e. transport across the Antarctic Slope Front). See our response to your next point below for more explanation. In the revised manuscript, we have attempted to better introduce this figure and its purpose within the manuscript (lines 204-209), among other changes elaborated on below.

o Can you provide some additional evidence and/or discussion that the water of this offshore reservoir is crossing the slope front. This might be as simple as linking to work that shows cross-shelf/slope exchange and adding in a sentence or two about the fact the slope current front is a barrier, but it is overcome.

As stated above, the intent of Figure 6 was to address this point, but it may have been unclear since we discussed the figure only briefly in the original manuscript. Figure 6b shows time series of the ocean surface stress curl in the central gyre (i.e. the gyre forcing) and the zonal wind anomaly offshore of the Amundsen Sea, which is thought to control the variability in cross-shelf exchange based on previous work (e.g. Dutrieux et al., 2014). This comparison shows that the wind conditions that favor gyre expansion also favor enhanced onshore transport at the slope. To better place our work in context, we have expanded our discussion of previous studies on cross-shelf exchange (lines 195-203), as well as our description of Figure 6 and its implications (lines 204-209, 214-218).

o Can you add the position of the Antarctic Slope Current Front to all of your map panels in your figures.

The Antarctic Slope Front (ASF) is not necessarily well-defined everywhere around Antarctica and we are not familiar with a standardized definition of its climatological position based on hydrography (Pauthenet et al., 2021). Often the 1000 m isobath is used to denote the climatological ASF (e.g. Thompson et al., 2018). We have plotted the 1000 m isobath as a thicker line than the other bathymetry contours in all figures and added to the figure captions that this corresponds approximately to the position of the ASF. However, if the reviewer has latitude/longitude values for the ASF position that they are willing to send us, we are happy to add it to the figures.

o L155: 'The meridional heat transport through this transect…' This transect is far from the slope, can you do the same calculation for a region at the slope for both the weak and strong cases? This would provide convincing evidence of the connection between the open ocean and shelf seas.

Thanks to the reviewer for this suggestion; this is similar to comments from the other reviewers as well. To address this point, we now explicitly show the temperature variability of the offshore region adjacent to the Amundsen continental shelf (Figure 6c) and the advective heat fluxes into this box (Extended Data Figure 4). Note that the box boundaries are defined to be consistent with past studies on onshore transport variability (e.g. Dutrieux et al., 2014). From these new plots we can see that, first, there is a clear warming of the offshore heat reservoir over the model run, particularly in the CDW density range. Second, this warming coincides with a zonal heat transport convergence that is primarily driven by an increase in the heat transport through the western face of the box, which corresponds to the pathway traveled by waters sourced from the gyre's eastern limb. This more quantitatively demonstrates the link between gyre variability and changes in the offshore heat reservoir, which we elaborate on in the text (lines 118-124, 187-190).

o In figure three, the meridional transect (black dashed line) is far from the edge of the gyre (green line). Why have you chosen to look there, as they seem far away and disconnected. I'd either move the transect close to the gyre edge, or explain why you have put it there (which I may have missed).

Our reason for placing the transect here was to show that temperature anomalies on the Amundsen Sea continental shelf (i.e. moving offshore from Thwaites and Pine Island Glaciers and thus relevant to melt rates) connect to anomalies that extend offshore. The motivation was that these offshore anomalies adjacent to Amundsen could be connected to the gyre, but this was not demonstrated explicitly and also relates to your comment above (and comments from all reviewers). We have attempted to better introduce this panel of the figure (lines 115-118) and more explicitly show a connection between the gyre and offshore heat reservoir through the additional heat transport calculation described above (see Figure 6c, Extended Data Figure 4 and text added at lines 118-124, 187-190).

(b) Errors and physical meaning of strong/weak years:

o For the gyre strength, can you make some estimate of the error.

• For a sensible (i.e. physically sensible) error, what about considering the time scale it takes for some heat anomaly to travel from the offshore reservoir to the slope edge. Say that is about a month(?), what is the monthly variability in gyre strength? Once you do have an error, could you add it to the plot in 2a and discuss what that means for your conclusions in the paper? You allude to this with this sentence here: 'We note that gyre anomalies cannot be instantaneously communicated to the shelf.'

We now calculate the variability in gyre strength within a given month using the barotropic streamfunction calculated from the model's 5-day velocity fields. We then use these 5-day estimates of gyre strength to calculate the standard error of the monthly means, which is now presented as error bars in Figure 2a. The main conclusions of our paper depend on qualitative differences in the gyre's eastern limb, rather than specific values of gyre strength and area, see additional explanation below.

• What if you choose a different Sverdrup contour?

The calculation of gyre strength (Figure 2a) and area (Extended Data Figure 2a) is the only piece of analysis that actually depends on the exact contour (aside from plotting the gyre boundary in various figures). The time series of gyre strength based on the -8 Sv contour is strongly correlated with that from other streamline thresholds (see the new Extended Data Figure 8).

Furthermore, our main conclusions are based on changes to the circulation that are reflected in the entire barotropic streamfunction (Figure 2b,c), so our results are insensitive to any particular gyre definition. We have added some discussion of this to the Methods section (lines 256-262).

o I'd recommend adding errors to your other important properties, like heat transport.

We use monthly estimates of the heat transport to calculate the standard error of the annual means, which is now presented as error bars in Figure 5b and Extended Data Figure 4. This is stated in the Methods section (lines 311-312).

(c) Looking forward and broader context: There has been some dramatic changes in the Southern Ocean recently. Can you add a few sentences to discuss how your work relates to possible longer-term changes and/or recent changes in sea ice?

Thanks for this suggestion. We have added mention of the recent sea ice extremes (lines 232-233). In terms of how this relates to our work, sea ice decline allows for a greater negative vorticity input by the winds, which leads to gyre expansion and strengthening. This, in turn, causes enhanced warming offshore of the Amundsen Sea continental shelf, which increases the potential for accelerated melt of the West Antarctic Ice Sheet. This is consistent with a recent paper that we cited (Gómez-Valdivia et al., 2023), and we have expanded upon this in the Conclusions section (lines 233-242).

o L250: 'gyre expansion is due largely to negative sea ice concentration anomalies in the region (Extended Data Fig. 3) rather than variability in the wind stress.' Cool, can you add some sentences along the lines of what the recent declines in sea ice may mean for the results of this study.

See our response above. Sea ice decline increases the vorticity input by the winds to the surface ocean, which leads to gyre expansion and strengthening. This, in turn, increases the heat supply to the region offshore of the Amundsen continental shelf, which could contribute to accelerated melt of the West Antarctic Ice Sheet if this coincides with similar or greater magnitude cross-shelf transport. We have expanded upon this in the Conclusions section (lines 232-242).

o L213 onwards: Could you spend a bit more time explaining what the limitations of the 6-year period of analysis are, specifically possible decadal trends.

There are known decadal and multi-decadal signals that may be relevant to the heat content of the Amundsen Sea continental shelf (e.g. Silvano et al., 2022; O'Connor et al., 2023). Furthermore, there is a trend in gyre strength and area over the entire model run in B-SOSE. This could be due to subsampling decadal fluctuations or a trend associated with anthropogenic forcing. Either way, characterizing the expanded and contracted gyre states within the model can provide mechanistic insight that is relevant to both the natural variability and forced trend. We have expanded our discussion of this in the text (lines 219-231).

o If it takes several years to get from one end of the gyre to the slope, what does that mean for the possible changes in heat transport onto the shelf?

There is a complex interaction of processes occurring over a range of timescales. Gyre-mediated changes in the offshore heat reservoir at the Amundsen Sea shelf break are likely relevant to multi-year or decadal variability, but may interact with the wind-driven variability in onshore CDW transport that has been studied in more depth (e.g. Dutrieux et al., 2014). We should be clear that we are not suggesting that the warming on the continental shelf is solely due to the gyre variability–changes in cross-shelf exchange and shelf circulation are also certainly important. However, variations in the offshore heat availability have not received much attention and could help explain some of the discrepancies in the literature about the impact of wind anomalies on CDW volume within the Amundsen Sea Embayment (see Silvano et al., 2022 and O'Connor et al., 2023). We have added discussion of these points (lines 192-203, 204-208) and generally tried to better frame our objectives in the revised manuscript (lines 51-55, 182-191, 214-218, 238-242).

Figure Comments:

Overall, the figures are clear and get the message across. A few design suggestions below to help improve clarity.

General,

- do the symbols in the figure captions need to be defined in each figure caption? Or replace the symbols with the name itself.

We tried adding the names to the figure; however, the text was very difficult to read. Therefore, we have retained the symbols but made sure to define them in the figure captions.

- The colour of the land, PF, and Sbdy change between figures. Could you keep them consistent?

The color of the land and fronts was changed between different figures in order to stand out against the colormaps used in that specific figure. For example, in Figure 1 the land is plotted in gray since black blends in more with the blue and purple of the underlying temperature and sea surface height contours. Conversely, in Figure 4 the land is plotted in black since gray creates confusion with the grayscale bathymetry contours. While we can appreciate the value of consistency across all figures, we still feel that the current choices increase the readability of the individual figures.

- The pink and orange of the PF and Sbdy is quite hard to see in some places.

We have adjusted the colors of the fronts, as well as the opacity of the velocity arrows and thickness of the bathymetry contours to help the fronts stand out better.

- Define 'Sbdy' and 'PF' acronyms. Even better, have their full names in the text.

We have added the acronyms to the relevant figure captions.

Figure 2:

- Can you add annotations for weak and strong gyre to the relevant place in 2a. I'd also add 'weak' and 'strong' next to the year label.

Thanks for the suggestion. We added annotations and labels for the weak and strong gyre years.

- Add the green boundaries from Fig. 3 to Fig 2.

We now highlight the -8 Sv contour (i.e. green boundaries in Figure 3) in purple in Figure 2.

Figure 3:

- I think it would be better to show some sort of temperature anomaly here, as the absolute temperature over 2013 to 2018 could be influenced by a trend.

Sorry for the confusion, Figure 3a did show the temperature anomaly relative to the mean value over the full model run. However, since we simply subtracted out the mean, this did not remove any trend. That said, in the revised manuscript we opted to remove Figure 3a since our intent is not to imply a direct connection between the temperature variability on the continental shelf and in the gyre at all time scales. Instead, the gyre variability is associated with multi-year changes in the heat content of the offshore reservoir adjacent to the Amundsen, so we now explicitly show the time series of temperature in this offshore region (Figure 6c).

- I'd make the purple and yellow stars bigger – the purple one is quite hard to find

As stated above, we have removed the previous Figure 3a, so the purple and yellow stars no longer appear in the other panels.

Extended Data 3:

- Explain what a negative value means (i.e. more sea in 2014) and what that means for gyre strength/shape.

Yes, a negative value means lower sea ice concentration in 2018. We have altered the figure caption to state this explicitly. Less sea ice allows for a greater negative vorticity input by the winds, which leads to gyre expansion and strengthening. This is expanded upon in the text (lines 232-233, 235-237).

Heat Transport plots:

- State in the caption what the transport is relative to and what the sign means.

We have altered the figure captions for Figure 5 and Extended Data Figure 6 following the reviewer's suggestion.

Particle Trajectory plots:

- Some small arrows and/or annotations to show the difference between the strong and weak years. These will aid the reader in following your conclusions.

You may be limited on space, but a schematic could be useful to add to the figure set.

We have adjusted the figure following the reviewer's suggestion.

Minor Comments:

Abstract: A few places where there is jargon. As this is being submitted to the nature journal family, it might be better to replace these words with those that are more accessible to general readers. For example, 'ocean surface stress curl'.

We have replaced "stronger ocean surface stress curl" with "wind and sea ice variability" in the abstract (lines 10-11). This is less precise technically speaking, but is more accessible to general readers and is more appropriate for the abstract. However, we retain the terminology "ocean surface stress curl" later in the paper, but with more explanation as to what this means (lines 85-89).

L19-21: I'd switch the order of these sentences to something like '…by the end of the century. So, determining its drivers is crucial to improve future sea-level and climate projections. However, ice shelf melt exhibits significant spatiotemporal variability.'

We have reordered the sentence following the reviewer's suggestion (lines 18-20).

L66: can you add this '1/6◦ nominal resolution' in km as well?

We have added "(~8 km)" to the sentence (line 66).

L67: 'Earlier iterations of this model have been used to investigate Ross Gyre transport33, 38 and its relationship to the thermohaline structure of the region.' Ok – and is the implication that B-SOSE is a reasonable representation of the Ross Gyre, if so can you state that please?

Yes, the intent of this statement was to express that the gyre circulation is well-represented in B-SOSE. We have added a sentence that states this explicitly (lines 68-69).

L69-71: Maybe this is too technical for the main bit of text here. I reckon that this statement would be better suited to the methods, and a statement like my comment above to replace it.

We added a statement like the one suggested above. However, we still feel that it's useful to mention the patterns in temperature on this density surface in the main text since this is context for understanding the temperature anomaly maps shown in Figure 3. Although we rewrote the sentence to make it less technical (lines 69-70).

L75: 'barotropic streamfunction' is a bit of jargon. And, its significance is not defined in the Methods. I'd suggest defining it when it first comes up in the

methods (e.g. 'Here, we define the position of the Ross Gyre using…') around L236. And adding something similar to the main text for further clarity.

The barotropic streamfunction represents the depth-integrated volume transport. We have added this clarification to the sentence where it is first introduced in the main text and in the Methods (lines 72-75, 252-254).

L88: a similar comment for 'ocean surface stress' . You have a very clear explanation in the methods (L245-252). Could you add something along the lines of '…ocean surface stress – the force applied to the ocean surface via wind and sea ice - …' in the Methods, as well as the first time ocean surface stress is used in the main text?

Thanks for the suggestion, we have altered the wording to the sentence where ocean surface stress is first introduced in the main text and in the Methods (lines 85-86, 263-266).

L94: At this location 'stronger cyclonic curl' is confusing. I see you explain it in L102-103. I suggest removing this sentence here, and ending the paragraph on the preceding statement re. high correlation.

We have rewritten the sentence to remove the phrase "stronger cyclonic curl." It now reads: "While the relationship between the strength of the forcing and the gyre transport is straightforward…" (lines 92-95).

L98: I was initially a bit confused by 'end-member years', what about 'case studies of contracted and expanded'.

We find the phrasing "end-member years" useful throughout the rest of the manuscript, however we have adjusted the wording of this sentence to more clearly introduce the terminology: "we select 2014 and 2018 (hereafter referred to as end-member years) as case studies of contracted and expanded gyre states, respectively." (lines 96-98).

L106: you could add 'blue shading' to '(Fig. 2c)' to be really clear.

We have added this to the parenthetical (line 105).

L112: I understand what you are saying, but perhaps a temperature anomaly would be better to show in Fig. 3a. And, what are you calculating the temperature anomaly (in the other panels) relative to?

Sorry for the confusion. Figure 3a did show the temperature anomaly relative to the mean value over the full model run. Since we simply subtracted out the mean, this does not remove any trend. However, this panel has been removed from the figure in the revised manuscript, as described previously. In all the panels we define the anomaly relative to the multi-year mean over the full run (2013-2018). We have added clarification of this to the text (lines 112-113) and figure caption.

L128: Why did you choose to run them backwards? Could you explain a bit more here what that means and why that choice was made? In other words, can you indicate where the particles were released, as well as their origin (which I think is different in this case)?

Many previous studies have investigated cross-shelf exchange processes by examining the heat flux across the 1000 m isobath (approximately the Antarctic Slope Front). The intent of the reverse particle release experiments was to provide context on the origin of the water masses that cross the 1000 m isobath. Variability in the pathways that are "upstream" of the ASF have received less attention, but are shown here to at least partially influence changes in cross-shelf heat transport. We have attempted to better contextualize our approach (lines 128-131, 137-140). The particle release locations are marked by orange and blue circles in Figure 4. The particles' origin is not prescribed, it is simply the location of the particle after 6 years of integration backwards in time.

L139: I'd start the paragraph with a topic sentence for example 'We used the strong and weak case study years to text the ….'. In general, a few of the paragraphs would benefit from a topic sentence at their start to help the reader along with the story.

We have added a topic sentence following the reviewer's suggestion and adjusted the wording of the following sentence as well. It now reads: "To assess how particle pathways are affected by gyre variability, we conducted two additional experiments based around the strong and weak end-member years. Namely, we used the same release locations…" (lines 141-144).

L145: '…not reflect realistic trajectories.' Good to state this. Instead, does it reflect a trend? If you feel confident in that, perhaps it would be interesting to add this here, or in your discussion?

The trajectories from the looped 2018 velocity experiment could be interpreted as a prediction of future pathways in the event that long-term sea ice decline leads to a systematic gyre expansion. We have added mention of this in our expanded discussion of future projections (lines 144-151, 232-237).

L147-152: I am confused by these statements. Just looking at Fig 4a and b (i.e. the trajectories), it looks like the weak gyre states provides more connection between the shelf and open ocean, because more of the particles cross the thick black line defining the shelf edge. I agree that there are more orange particles further east in the strong case (Fig. 4c), but I do not follow how you have concluded the rest of the sentences. I think that this section needs work to clarify what you mean. Also see my first major comment.

The purpose of our study is to highlight mechanisms of variability to the heat reservoir offshore of the shelf break, since these have largely been ignored in the literature, rather than cross-shelf exchange. Of course, the motivation for understanding this offshore heat content is due to its potential to be brought onto the shelf, but the model is too coarse to represent some processes relevant to cross-shelf exchange, hence why we focus on the remote pathways of heat transport to the continental slope. In this sentence we are referring to the fact that there is a more direct connection between the release location in the Amundsen (orange dot in Figure 4a,c) and the gyre in the expanded state (Figure 4c) due to the position of the gyre's eastern limb. Whereas in the contracted state (Figure 4a) the waters that reach the Amundsen have taken a more circuitous path around the Marie Byrd seamounts and thus experience more water mass transformation and cooling before reaching the shelf. We have expanded our explanation of this figure in the text (lines 147-153).

L185: At the moment this statement is a bit strong, given my first major comment.

We have softened the statement (lines 187-191) and generally tried to better frame our objectives in this study as described earlier in response to your first major comment (lines 51-55, 182-186, 214-218, 238-242).

Conclusions: I have not focused too much on the conclusions for now, as I think this section may change given my comments above. However, I do think that there is some jumbling between: i) what you have done, ii) what others have done, iii) implications, and iv) caveats. I recommend a re-arrange, so that you have a few paragraphs along the lines of: i) what you found, ii) what the implications of your work are, iii) placing that in the context of others, iv) caveats, v) overall conclusions and implications.

We have rearranged and rewritten large parts of the Conclusions section. We have tried to generally follow the suggested structure. Our paragraphs can be roughly categorized as: (i) summary of what we have done, (ii) summary of what others have done, (iii) how our results relate to previous work, (iv) caveats, (v) implications for the future. However, in attempting to put our results in conversation with past work, there is still some degree of mixing of our results with what others have done and the implications that this has.

REVIEWER 2

We sincerely appreciate the reviewer's comments, which are copied in bold below. The following are our point-by-point responses.

Prend et al use a state-of-the-art data-assimilation model (B-SOSE) to analyse the role of the Ross Gyre in delivering ocean heat toward West Antarctica, where ice shelves are rapidly melting due to warm Southern Ocean waters. I find the manuscript very interesting, especially because much of the focus to date has been on local drivers of ice shelf melting in the Amundsen Sea, while we expect that large scale ocean circulation can play a key role, especially on long time scale. The analysis is appropriate, the manuscript well written and the topic highly relevant to the climate science community and beyond. I have one main comment and few minor comments below.

Main Comment

- **Line 179-188: If the particles take years to get from the Ross Gyre to the shelf**

break of the Amundsen Sea, we could imagine that "interannual signals" of the gyre strength could be dampened, and therefore we might need to think in terms of decadal (or longer) variability. Also, how modelled warming in 2018 on the Amundsen Sea continental shelf can be caused by gyre variability if it takes years to propagate? And related to this, you show along isopycnal warming, suggesting some role of isopycnal mixing. Is there a role for isopycnal heaving? I would add a paragraph to discuss about these points, potentially highlighting some further caveats due to the simulation period (6 years).

Yes, we agree that the differences between the end-member years reflect processes that may vary over a range of temporal scales, including decadal or multi-decadal. The function of the end-member years within our study is to characterize the dynamics associated with expanded and contracted gyre states, not to suggest that this is explicitly an interannual signal. For example, the model shows a trend towards gyre expansion over the full simulation period, so our intent is to link the anomalies on the continental shelf in 2018 to a multi-year gyre-mediated warming of the offshore heat reservoir (adjacent to the Amundsen), rather than variations in the gyre circulation in that year specifically. We have attempted to better clarify this in the text (lines 121-124, 225-231) and now explicitly show the variability in the offshore temperature (Figure 6c) and connect this to zonal heat transport convergence that is consistent with the gyre variability (Extended Data Figure 4).

Also, we are not suggesting that the warming on the continental shelf is solely due to the gyre variability. The anomalies on the continental shelf also reflect variations in the onshore transport, which we elaborate on below in our response to your comment about the undercurrent. Isopycnal heaving could play a role in the cross-shelf flux variability by altering the depth of the thermocline at the continental slope (Moorman et al., 2023). However, the temperature anomalies that we examine in this study (Figure 3) are isopycnic and thus independent of changes in the isopycnal depth. We have attempted to better frame our objectives in the revised manuscript (lines 51-55, 182-186), and added text addressing these points to the Conclusions section (lines 214-218, 238-242).

Minor Comments

• Extended Data Figure 1. I would mention in the caption what the dotted black box represents.

The dotted black box marks the region that we averaged over for the time series of ocean surface stress curl plotted in Figure 2a (i.e. the region that forces the gyre). We have added this to the figure caption.

• Line 97-111: Would it be possible to extract the wind stress curl and compare it between 2014 and 2018. This to understand whether the difference in sea ice is the cause of the difference between the 2 years.

Yes, the gyre strength and area are more strongly correlated with the ocean surface stress curl (Figure 2a) than with the wind stress curl alone (consistent with Dotto et al., 2018). In other words, the sea ice concentration anomalies between the two years (Extended Data Figure 3) are central to understanding the gyre variability. Sea ice decline increases wind energy input to the surface ocean, which leads to gyre expansion and strengthening (consistent with Gómez-Valdivia et al., 2023). This has implications for future changes to the gyre and resulting pathways of heat transport under anthropogenic forcing. We have expanded our discussion of these points in the text (lines 232-242).

• What bathymetry is used in the model?

The bathymetry used in the model is ETOPO1 (Amante & Eakins, 2009); we have added this to the Methods section (line 250).

• Line 189-202: looking at Figure 4, it seems that the model has a weak undercurrent at the shelf break (or maybe a westward flow in the CDW layer). Is this correct? Maybe it depends on the release location. In case the undercurrent is not captured by the model, would this have implication on your conclusions about the role of the Ross Gyre?

The undercurrent at the shelf break is present intermittently in the model but is not a persistent feature. This is potentially representative of the real undercurrent since knowledge of its presence is based on limited in situ measurements (Walker et al., 2013). The role of the undercurrent in controlling cross-shelf exchange is complex and not agreed upon (St-Laurent et al., 2013; Silvano et al., 2022). However, our focus in this study is to highlight mechanisms of variability to the offshore heat reservoir, since these have largely been ignored in the literature, rather than cross-shelf exchange. The motivation for understanding this offshore heat content is its potential to supply heat to the shelf, but the model representation of the undercurrent does not influence the remote (i.e. open ocean) pathways of heat transport that we seek to investigate in this study.

The intent of Figure 6 was to place the gyre variability within the context of the known variations in cross-shelf exchange (independently of the model's explicit representation of cross-shelf fluxes). But this may have been unclear since we only discussed it briefly in the original manuscript. Figure 6b shows time series of the ocean surface stress curl in the central gyre (i.e. the gyre forcing) and the zonal wind anomaly offshore of the Amundsen Sea, which is thought to control the variability in cross-shelf exchange based on previous work (e.g. Dutrieux et al., 2014). This comparison shows that the wind conditions that favor gyre expansion also favor enhanced onshore transport at the slope, which again is independent of the model's representation of the undercurrent. To better contextualize our work, we have expanded our discussion of previous studies on cross-shelf exchange (lines 195-203, 238-242), as well as our description of Figure 6 and its implications (lines 204-218).

REVIEWER 3

Thanks to Dr. Rintoul for his kind and thorough review of the paper. Significant thought was clearly put into the comments, which are copied in bold below, and followed by our point-by-point responses.

This is an interesting and highly relevant paper, given the societal importance of understanding the future of the Antarctic Ice Sheet and its vulnerability to ocean

heat. The paper shows that the size and strength of the Ross Gyre respond to changes in surface stress over the gyre. Stronger forcing drives expansion of the gyre, which alters the circulation pathways near the Antarctic continental shelf. An expanded gyre means that more water flows east to the Amundsen Sea after the poleward limb of the gyre bifurcates on reaching the continental slope. The authors argue this increases the reservoir of heat offshore of the Amundsen Sea and therefore allows more heat to reach the continental shelf where it can drive enhanced basal melt of ice shelves.

The analysis provides a compelling case that the size and strength of the gyre responds to changes in surface stress and that an expanded gyre results in a more direct pathway from the open ocean to the Amundsen Sea continental shelf. However, a key part of the story seems to be missing: the analysis stops short of showing that these changes alter the reservoir of heat offshore of the Amundsen Sea continental shelf. (The paper does show that the expanded gyre state coincides with warm anomalies at the shelf break and on the continental shelf, but these anomalies are not shown to be related to the mechanism proposed in the paper, as discussed in more detail below.)

**To some extent, the paper wants to have it both ways: the authors argue on the one hand that SOSE is not the right tool to look at changes in heat over the continental shelf, as it is missing some key processes that transport heat across the shelf break and across the continental shelf; on the other hand, the title and concluding comments make an explicit connection between variations in the Ross Gyre and the heat supply to the continental shelf and ice shelves. The language might need some slight adjusting in places to avoid overreach.
If variations in the gyre can be tied more directly to changes in the heat reservoir offshore of the Amundsen Sea, then the paper will be suitable for publication and will make a valuable contribution to the ongoing discussion of processes regulating the delivery of ocean heat to the Antarctic continental shelf.**

These are fair points, and similar to comments from the other reviewers as well. We now explicitly show the warming of the offshore reservoir adjacent to the Amundsen (Figure 6c), which coincides with a zonal heat transport convergence (Extended Data Figure 4) that is consistent with an increase in transport along the gyre-mediated pathway to the Amundsen. This more quantitatively demonstrates the link between gyre variability and changes in the offshore heat reservoir, which we elaborate on in the text (lines 118-124, 187-190).

We have also softened our language in several places to avoid overreach (lines 53-55, 190-191). To be clear, we are not suggesting that the warming on the continental shelf is solely due to the gyre variability–changes in cross-shelf exchange and shelf circulation are also certainly important. But we believe that variations in the offshore heat availability have not received enough attention and could help explain some of the discrepancies in the literature about the impact of wind anomalies on CDW volume within the Amundsen Sea Embayment (see Silvano et al., 2022 and O’Connor et al., 2023).

The intent of Figure 6 was to place the gyre variability within the context of the known variations in cross-shelf exchange, independently of the model's explicit representation of cross-shelf fluxes. But this may have been unclear since we only discussed it briefly in the original manuscript. Figure 6b shows time series of the ocean surface stress curl in the central gyre (i.e. the gyre forcing) and the zonal wind anomaly offshore of the Amundsen Sea, which is thought to control the variability in cross-shelf exchange based on previous work (e.g. Dutrieux et al., 2014). This comparison shows that the wind conditions that favor gyre expansion also favor enhanced onshore transport at the slope. We have attempted to better frame our objectives and contextualize our work in terms of previous studies on cross-shelf heat fluxes (lines 195-203, 238-242), as well as our description of Figure 6 and its implications (lines 204-218).

Specific comments:

The authors show that the main difference between contracted and expanded gyre states is the stress driving the ocean, which in turn depends heavily on sea ice. If the gyre controls heat delivery to the shelf, and the strength of the gyre depends on sea ice cover, this implies that sea ice anomalies in the open ocean modulate heat delivery to the shelf. This might be worth highlighting.

Agreed. This is also consistent with a recent paper that we cited (Gómez-Valdivia et al., 2023). We have emphasized this point more explicitly in the Conclusions section (lines 235-237).

The particle tracking does a good job of illustrating the change in circulation between the contracted (2014) and expanded (2018) gyre states. In particular, it's clear that a larger fraction of particles head east to the Amundsen Sea in the expanded gyre state. But the paper does not provide much evidence to support the overarching conclusion that changes in the Ross Gyre modulate the heat supply to the West Antarctic continental shelf. For example, there is no quantitative analysis of the change in heat content of the off-shelf reservoir and of its dependence on changes in the Ross gyre. A quantitative heat budget for a closed volume offshore of the Amundsen Sea shelf break might be useful; if the proposed mechanism holds up, I guess there should be larger eastward heat flux entering the box through the western boundary, and an increase in the off-shelf heat reservoir. Heat flux across a short transect between 130W and 135W is shown, but this is a long way from the West Antarctic shelf. Calculations of the heat transport across additional sections along the pathway identified by the particle trajectories might be done to show that the stronger/expanded gyre does indeed carry more heat to the Amundsen Sea shelf break.

As stated in our response to your first major point, we now explicitly show the temperature variability of the offshore reservoir adjacent to the Amundsen (Figure 6c) and the advective heat fluxes into this box (Extended Data Figure 4). We define the offshore reservoir using boundaries that are consistent with past studies of onshore transport variability (e.g. Dutrieux et al., 2014). From these new figures we can see that, first, there is a clear warming of the offshore heat reservoir over the model run. Second, this warming coincides with a zonal heat transport convergence that is primarily driven by an increase in the heat transport through the western face of the box. This is consistent with an increased supply of CDW sourced from the gyre's eastern limb. While we have not closed a full heat budget, this does more quantitatively demonstrate the link between gyre variability and changes in the offshore heat reservoir, which we now discuss in the text (lines 118-124, 187-190).

It's not so clear to me why the 27.9 neutral density surface is used to illustrate changes in CDW. The text suggests this is "the core" of CDW (line 70), but it's not clear what it meant by "core". The CDW (upper and lower) spans a wide depth and density range. Water properties on the 27.9 surface are quite different from slightly denser isopycnals that also lie within the CDW layer (at least in the observations, and presumably in SOSE). The 27.9 surface has a very strong temperature gradient along the isopycnal (as illustrated in Fig 1), because the isopycnal shoals to approach the surface in the Ross Gyre. Based on neutral density sections on WOCE P15 or WOCE S4-Pacific (e.g. http://woceatlas.tamu.edu/images/printed/jpg/S4_gam_right.jpg), this isopycnal sits in the T-min layer in the Ross Gyre, suggesting it outcrops in winter. This is not really CDW anymore – it has had its water properties heavily modified by interaction with the winter atmosphere (i.e. is now Antarctic Surface Water). Where the isopycnal deepens on the edge of the gyre (near 145W on S4), the temperature rapidly increases. I think this explains the large temperature anomalies on this isopycnal around the rim of the gyre when the gyre expands or contracts (Fig. 3). You would get a very different picture if you used a neutral density surface in the CDW layer that did not outcrop in winter, but did access the continental shelf in the Amundsen Sea.

This doesn't mean that 27.9 is a bad choice – the strong isoneutral temperature gradients mean that expansion or contraction of the gyre gives the strongest temperature signal on this isopycnal – but the choice needs to be justified. This justification should make clear whether this isopycnal is chosen to illustrate expansion or contraction, or because it is particularly relevant to the issue of heat transport to the Amundsen Sea. If the latter was true, this would be strong justification for using this density surface, but I can't see how this is the case.

By "core" of the CDW layer, we were referring to the fact that this density surface corresponds to the subsurface temperature maximum at the shelf break in the Amundsen (specifically, at the release location for the reverse trajectories marked by an orange circle in Figure 4). This is now stated explicitly in the Methods section (lines 274-276). However, it is certainly true that the subsurface layer of warmer temperatures at this location is quite broad and spans a range of depths/densities (see Figure 4b). In the model, the 27.9 surface does outcrop in winter in a small region within the central gyre (see the new Extended Data Figure 9). Although this does not correspond to the locations with the largest isopycnic temperature anomalies, which occur due to the shifting of the temperature gradient near the gyre edge. There is a strong isopycnal temperature gradient even for density surfaces that do not ever outcrop at the surface, and so the temperature anomaly patterns look qualitatively similar for denser surfaces as well (see the new Extended Data Figure 10).

The 27.9 surface was selected both because it illustrates how the expansion/contraction of the gyre manifests itself in the along-isopycnal temperature structure and because it corresponds to the subsurface temperature maximum at the shelf break (which by extension suggests its relevance to the issue of heat transport to the Amundsen). However, we do not think that any of the conclusions of the paper depend on the selection of this particular density surface. We have added a discussion of these points to the Methods section (lines 276-287).

There is also no justification provided for the choice of 130 to 135W, 67S as the place to look at heat transport by the gyre. Is the poleward heat transport by the eastward limb of the gyre sensitive to this choice? In the Abstract, it says "Gyre expansion, linked to stronger ocean surface stress curl, increases poleward CDW volume transport along the gyre's eastern limb and the subsequent heat transport toward the Amundsen Sea and the WAIS." This short section does not span the entire eastern limb of the gyre in either the contracted or expanded states, so I don't believe a comparison of heat transports across the short section is sufficient to support this conclusion.

This is a fair point. However, our intent is not to assign a precise value to the heat transport, but rather to compare the two years. In the new Extended Data Figure 11, we show that the poleward heat transport by the gyre's eastern limb is enhanced in 2018 (expanded gyre) relative to 2014 (contracted gyre) regardless of the precise location or width of the transect (although the longitude of maximum transport does change). This is because the enhanced heat transport is driven largely by the velocity anomalies, and there is a close correlation between gyre size and strength (Extended Data Figure 2a). This is discussed in the Methods section (lines 305-309).

In the abstract, it says "Strong temperature variability on CDW density surfaces occurs at interannual timescales due to the redistribution of heat between the gyre and continental shelf." I don't believe any evidence is provided in the paper to support this statement, as there is no quantitative analysis of heat content or transport (except across the short control section between 130 and 135W). The strong temperature anomalies around the rim of the gyre do not necessarily imply a redistribution of heat: they could reflect movement of the sharp gradient of temperature along the 27.9 surface near the gyre edge, as noted above. If the argument is that, in the expanded state, cooling around the gyre rim is the result of heat being advected away from the gyre and onto the continental shelf, I think this is unlikely to be correct. (Would the authors argue the reverse is true for the contracted state: that heat advection from the continental shelf to the edge of the gyre explains cooling on the shelf and warming around the rim of the gyre?) Perhaps I am missing the point, but if this is indeed the argument, it requires a quantitative demonstration (and if I am missing the point, the point needs to be clarified).

Yes, this statement was worded poorly. We fully agree that the strong temperature anomalies around the rim of the gyre reflect the movement of the sharp temperature gradient at the gyre edge (which occurs on this isopycnal, but also on others). Our statement about the redistribution of heat between the gyre and the continental shelf is actually not motivated by the isopycnic temperature anomalies, so this sentence was misleading. Apologies for that! The redistribution of heat between the gyre and continental shelf is supported by the difference in the partitioning of particles between the gyre and Amundsen pathways shown in Figure 5d, as well as the new figure showing heat transports into the offshore reservoir (Extended Data Figure 4). We have removed this sentence and replaced it with a new one that more accurately describes what was shown in the paper (lines 8-10).

Figure 3 is a key figure because it is the only one that shows information about temperature anomalies, and so is central to the argument that variations in the gyre modulate heat transport to the Amundsen continental shelf. But I am not sure it really supports the argument very well. The maps in panels (b) and (d) are dominated by the temperature anomalies around the rim of the gyre and on the continental shelf. In contrast, temperature anomalies are weak along the flow path inferred from the particle trajectories. In Fig. 5, it is shown that the increase in heat transport across 130-135W @ 67S is mostly due to stronger velocities, rather than warmer temperatures, so it might not be a surprise that this advective pathway does not show up clearly in a map of temperature anomalies. This is why a direct analysis of changes in heat content near the Amundsen Sea is needed to provide stronger support for the hypothesis.

Panels (c) and (e) also don't support very strongly the argument that advection of heat from offshore drives warming on the shelf. The sections show strong warming in the expanded gyre case at the shelf break, with strongest warming above the 27.9 isopycnal, but weaker warming offshore. If advection along the long pathway from the Ross gyre is the driver of changes in offshore heat content, why is the warming enhanced over the shelf break? Could other mechanisms (e.g. wind-driven changes in the Antarctic Slope Front) drive the strong temperature anomalies over the shelf break and on the continental shelf? I'd encourage the authors to look more carefully at the origin of the temperature anomalies over the shelf break and on the shelf. Can they be unambiguously attributed to advection of heat from the Ross Gyre?

Thank you for these questions, as we found them to be very thought provoking! Some of these points we have already responded to, but to reiterate, we now explicitly show the warming of the offshore reservoir (Figure 6c), which results from a zonal heat transport convergence (Extended Data Figure 4) that supports the link between gyre variability and offshore heat content (lines 118-124, 187-190). In terms of how or whether the offshore anomalies propagate onshore, this is an interesting question that is the subject of ongoing work. To clarify, we are not suggesting that the warming on the continental shelf is solely due to the gyre variability–changes in cross-shelf exchange, and specifically wind-driven changes in the Antarctic Slope Front are undoubtedly important. As described previously, the intent of Figure 6 was to put the gyre variability in conversation with the wind-driven onshore transport variability that has been investigated more thoroughly. We have attempted to better frame our objectives and contextualize our work (lines 51-55, 182-186), as well as our description of Figure 6 and its implications (lines 204-218). But as stated earlier, we believe that variations in the offshore heat availability have not received enough attention and could help explain some of the discrepancies in the literature about the impact of wind anomalies on CDW volume within the Amundsen Sea Embayment (Silvano et al., 2022 and O'Connor et al., 2023).

Line 52: "The off-shelf heat availability to the WAIS is, therefore, regulated by interannual variations in the gyre circulation," But 'off-shelf heat availability' is never shown?

Yes, good point. This was insinuated but not shown in the original manuscript. As described previously, we now show the time series of temperature in the offshore reservoir (Figure 6c) and the advective heat transports into this box (Extended Data Figure 4). Warming of this reservoir corresponds to an increase in the heat transport through the western face (i.e. from the gyre). More discussion of this has been added to the text (lines 118-124, 187-190).

Line 118: "We note that gyre anomalies cannot be instantaneously communicated to the shelf. Still, the time series of CDW temperature in the central gyre and in the Amundsen Sea display opposing trends over the 6-year model run (Fig. 3a). By following a meridional transect offshore from Pine Island and Thwaites glaciers, we also find that temperature anomalies on the Amundsen shelf connect smoothly to offshore anomalies" Fig 3a is not very convincing – there could be other causal factors (e.g. changes in the Antarctic Slope Front), especially as elsewhere it is stated this model is not well-suited to simulating changes in the processes carrying heat onto the continental shelf (so why show a shelf water time series?). As noted above, Fig 3b does not really show a "smooth" connection between on- and offshore – rather a strong maximum at the shelf break, with much weaker anomalies offshore.

Agreed. Our intent was not to imply that the temperature anomalies on the continental shelf are solely the result of variability in the remote gyre-mediated pathways. Our goal with this study is to highlight mechanisms of variability to the offshore heat reservoir since these have largely been ignored in the literature. However, we agree that changes in the offshore reservoir are just one piece of the story in terms of controlling the variability in the continental shelf heat content, which will also depend on the onshore transport (and shelf circulation). The purpose of our Figure 6 was to try to place the gyre variability within the context of the known variations in cross-shelf exchange (and independent of the representation of cross-shelf exchange processes in B-SOSE). The comparison of ocean surface stress curl in the central gyre (i.e. the gyre forcing) and the zonal wind anomaly offshore of the Amundsen Sea (i.e. variability in cross-shelf exchange based on previous work) shows that the wind conditions that favor gyre expansion also favor enhanced onshore transport at the slope. So these mechanisms are likely acting in concert. In order to clarify these points, we have expanded our discussion of previous studies on cross-shelf exchange (lines 192-203), as well as our description of Figure 6 and its implications (lines 204-218).

Line 154: "along a transect that extends from 130 to 135◦W at 67◦S—capturing the core of the gyre's eastern limb" does it cross the "core" of the eastern limb in both the contracted and expanded states? (or is heat transport higher in expanded state because more of the gyre occurs in this longitude band?)

This is a warranted question. Yes, we intentionally selected the transect location to cross the core of the eastern limb in both the expanded and contracted states. Furthermore, the main result–that 2018 had a greater southward heat transport–is insensitive to the transect length and precise location (see new Extended Data Figure 11). This is not so surprising given that the difference in heat transport between the end-member years is primarily due to the velocity anomalies (Extended Data Figure 6), which are consistent over a large region as evidenced by the comparison of the barotropic streamfunction between the two years (Figure 2). This is now mentioned in the Methods section (lines 305-309).

Line 203: "We have demonstrated that Ross Gyre variability can modulate the offshore heat reservoir adjacent to the Amundsen Sea at interannual timescales and thus deserves further investigation in the context of WAIS melt". But there are no plots or analyses of the offshore heat reservoir changes with time?

As described already, we now show the offshore temperature variability (Figure 6c) and the advective heat fluxes that contribute to this variability (Extended Data Figure 4). More discussion of this has been added to the text (lines 118-124, 187-190).

Line 224: "Furthermore, an expanded gyre implies enhanced melting of the most vulnerable ice shelves in West Antarctica" Up until now, the authors have been suitably cautious, given that SOSE is not believed to capture the processes that may control how much heat crosses the shelf break and ultimately reaches the ice shelf. But here they draw a direct link between the gyre and basal melt, a link not supported by the evidence provided.

Steve Rintoul

We did not mean to suggest that the gyre variability is the dominant driver of melt rate variability, and our use of the word "implies" was intended to convey the uncertainty of this statement. Naturally, the melt rates will ultimately depend on the heat that is supplied to the ice shelf cavities. Our argument is simply that the gyre variability is a mechanism that could contribute to the heat content variability on the continental shelf, which in turn influences basal melt. We agree that we have not demonstrated a direct link between the gyre and basal melt, although this remains the underlying motivation for this work and, we believe, is worth mentioning in the context of the implications of our results. However, we have adjusted the wording of the sentence to prevent overreach and make it clear what we have shown versus what we are speculating (lines 238-240).

14th Dec 23

Dear Dr Prend,

Your manuscript titled "Ross Gyre variability modulates oceanic heat supply to the West Antarctic continental shelf" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

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

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Prend et al have carefully addressed the comments from myself (as well as two other reviewers). Their paper has improved. In particular, the objectives are clearer and the conclusions more convincing. I only have some minor comments, as shown below, otherwise I think it is ready to be published. Well done!

Minor Spelling/Grammar Suggestions below (line numbers based on the tracked change article)
- L15: ‘Ross Gyre variability, therefore, influences oceanic heat supply to the continental slope,’, replace ‘to’ with ‘toward’
- L58: delete ‘the’ before ‘heat delivery’
- L59L: stick in a couple of references there?
- L74: ‘and its relationship’… are there some refs missing at the end there?
- Various: a few broken references coming up as ‘?’
- In some of the figure captions, you say ‘Polar Front PF’ and in some of them you say ‘Polar Front (PF)’, I’d use the latter.
- Extended Data Fig 4. It may be more clear to plot the x-axis for each of the panels at the same

range (e.g. -5 to 5 TW). Then the reader can quickly see where the heat is moving around the different faces of the reservoir.
- Extended Data Fig 11. The longs are plotted on difference scales, e.g. one is -180 to 180 and the other is 0-360.

P.S. I do not have lat/longs for the ASF. I was hoping that the guideline positions shown in Thompson et al (2018) would be used, as you have done.

Reviewer #2 (Remarks to the Author):

The authors have addressed my comments and I recommend this study to be published. It is an important advance to our understanding of the Ross-Amundsen Sea system. I have one final suggestion. What about slightly modifying the title of the manuscript to better reflect what is shown in the study? The heat transport onto the continental shelf is not much discussed. Instead the focus is on the heat delivery toward the continental slope of the Amundsen Sea or, more in general, toward the Amundsen Sea.

Reviewer #3 (Remarks to the Author):

I congratulate and thank the authors for their careful response to the reviews. I am happy with the revision and recommend the paper for publication as is. I think the calculation of the difference in heat advection in the contracted and expanded state helps the argument.

However, I do have a few points the authors might consider.
I still feel the title perhaps promises a bit more than the paper delivers (the paper doesn't quite show that the heat supply to the continental shelf is regulated by variability of the Ross Gyre), but I wouldn't push it. "… heat supply to the West Antarctic continental shelf break" might capture the topic covered here more accurately, but I'll leave it to the authors to make a change if they wish. (Also line 186.)

Line 188: "An expanded gyre preferentially steers heat toward the Amundsen and Bellingshausen Seas…" When I read this line this time around, I thought "that's interesting, I guess the Ross Sea must cool in the expanded state." But Figure 3 shows that the eastern Ross Sea also warms. Warming of more or less the entire continental shelf in the expanded state suggests there is more going on than shunting of more heat to the east when the gyre is in its expanded state. But maybe this is a topic for another day.

Line 206: The text points out that surface stress curl over the central gyre and zonal wind anomalies at the Amundsen shelf break are "weakly correlated (r=0.19)" and suggest therefore that the expanded gyre state may also be associated with stronger on-shelf transport. But given the relationship explains 4% of the variance, wouldn't a more appropriate conclusion be that the two are essentially uncorrelated and there is no significant relationship between the surface stress curl over the gyre and wind-driven on-shelf transport?

Thanks to the reviewers for their positive feedback on our revised manuscript. This has been a very constructive review process, and we are sincerely grateful for the time and effort put in by all of the reviewers. We have implemented all of the minor remaining comments, detailed below, in the final version of the manuscript.

REVIEWER 1

Prend et al have carefully addressed the comments from myself (as well as two other reviewers). Their paper has improved. In particular, the objectives are clearer and the conclusions more convincing. I only have some minor comments, as shown below, otherwise I think it is ready to be published. Well done!

Thanks for the encouragement, your review greatly improved the paper! Line numbers in our responses below correspond to the final (i.e. non-track changes version), so are slightly different from the line numbers given by the reviewer.

Minor Spelling/Grammar Suggestions below (line numbers based on the tracked change article)

- L15: 'Ross Gyre variability, therefore, influences oceanic heat supply to the continental slope,', replace 'to' with 'toward'

We replaced "to" with "toward" (line 11).

- L58: delete 'the' before 'heat delivery'

We deleted "the" before "heat delivery" (line 51).

- L59: stick in a couple of references there?

We added references to and Morrison et al. (2020), Tamsitt et al. (2021), and Dawson et al. (2023) (line 52).

- L74: 'and its relationship'… are there some refs missing at the end there?

Thanks for catching this! The references in the middle of the sentence after "transport" should have been placed at the end of the sentence. This has been fixed (line 66).

- Various: a few broken references coming up as '?'

We fixed the references in the final version.

- In some of the figure captions, you say 'Polar Front PF' and in some of them you say 'Polar Front (PF)', I'd use the latter.

We have ensured that "Polar Front (PF)" appears in all relevant figure captions.

- Extended Data Fig 4. It may be more clear to plot the x-axis for each of the panels at the same range (e.g. -5 to 5 TW). Then the reader can quickly see where the heat is moving around the different faces of the reservoir.

While we appreciate the reviewer's point, one of the main takeaways from the figure is the zonal and meridional heat convergences rather than the values through each individual face. In this sense, comparing panels (a) and (b) to each other (i.e. zonal heat convergence), and comparing panels (c) and (d) to each other (i.e. meridional heat convergence) is the most important thing for the purposes of our manuscript. This is why we opted to plot panels (a) and (b) on the same x-axis range and panels (c) and (d) on the same x-axis range, rather than using the same axis limits for all four of the panels.

- Extended Data Fig 11. The longs are plotted on difference scales, e.g. one is -180 to 180 and the other is 0-360.

We have adjusted x axis in panel (b) to use the same longitude scale (-180 to 180).

REVIEWER 2

The authors have addressed my comments and I recommend this study to be published. It is an important advance to our understanding of the Ross-Amundsen Sea system. I have one final suggestion. What about slightly modifying the title of the manuscript to better reflect what is shown in the study? The heat transport onto the continental shelf is not much discussed. Instead the focus is on the heat delivery toward the continental slope of the Amundsen Sea or, more in general, toward the Amundsen Sea.

Thanks for your positive comment! We agree regarding the manuscript title and have replaced "to the continental shelf" with "toward the continental shelf."

REVIEWER 3

I congratulate and thank the authors for their careful response to the reviews. I am happy with the revision and recommend the paper for publication as is. I think the calculation of the difference in heat advection in the contracted and expanded state helps the argument.

Thanks for the encouragement, your review greatly improved the paper!

However, I do have a few points the authors might consider.
I still feel the title perhaps promises a bit more than the paper delivers (the paper doesn't quite show that the heat supply to the continental shelf is regulated by variability of the Ross Gyre), but I wouldn't push it. "… heat supply to the West Antarctic continental shelf break" might capture the topic covered here more

accurately, but I'll leave it to the authors to make a change if they wish. (Also line 186.)

We appreciate this point, which was also raised by Reviewer 2. We have replaced "to the continental shelf" with "toward the continental shelf" in the manuscript title to address this. Additionally, line 185 now reads "toward" instead of "to" the continental shelf.

Line 188: "An expanded gyre preferentially steers heat toward the Amundsen and Bellingshausen Seas…" When I read this line this time around, I thought "that's interesting, I guess the Ross Sea must cool in the expanded state." But Figure 3 shows that the eastern Ross Sea also warms. Warming of more or less the entire continental shelf in the expanded state suggests there is more going on than shunting of more heat to the east when the gyre is in its expanded state. But maybe this is a topic for another day.

This is an interesting point that we did consider. The overall gyre heat transport increases in the expanded state (Figure 5b; Extended Data Figure 6,11). This is indeed associated with an increase in the fraction of heat moving toward the Amundsen Sea (Figure 5d), but there is still also a greater total heat transport to the Ross Sea in the expanded state compared to the contracted state (due to the overall greater gyre transport). The strengthened gyre also provides a more direct pathway between the open ocean and the Ross due to reduced meandering in the along-slope flow after the bifurcation at the Marie Byrd seamounts, which increases the subsurface temperature maximum at the shelf break. This is now mentioned at lines 148-152.

Line 206: The text points out that surface stress curl over the central gyre and zonal wind anomalies at the Amundsen shelf break are "weakly correlated (r=0.19)" and suggest therefore that the expanded gyre state may also be associated with stronger on-shelf transport. But given the relationship explains 4% of the variance, wouldn't a more appropriate conclusion be that the two are essentially uncorrelated and there is no significant relationship between the surface stress curl over the gyre and wind-driven on-shelf transport?

This is a fair point; the relationship is unclear and deserves further investigation. Future work should consider how changes in gyre circulation interact with the processes that enable cross-shelf exchange across a range of timescales, which is now stated at lines 215-217.