

Reviewer 1

Thank you for the very helpful feedback on our manuscript, which will strengthen the review. In particular we appreciate the suggestion to add more structure and uniformity to the sections, and to add more figures. Below we provide responses to the individual comments.

[General comments]

In this manuscript, the authors comprehensively survey numerous papers on the role of sea ice in the Southern Ocean in the climate system, and succeeds in collecting vast amounts of information on the topic. The authors' attempt to provide an excellent overview on the issue surely has a potential to be appreciated by scientists of diverse research fields, and in particular, their effort to discuss how sea ice has interacted with other subsystems during past large-scale climate changes from a paleoclimatological perspective should be a novel and scientifically worthwhile conception. However, I have to raise serious concern that the specific methods used to organize the research findings and the manner to present them to readers are not necessarily optimal. The manuscript tries to cover vast amounts of phenomena and information; of necessity, the authors should pay close attention to methods for organizing and communicating them. I am certain that this manuscript will be dramatically improved and will realize its potential with a proper methodology to convey the authors' arguments in a clear and accessible manner. In addition, I also point out that the manuscript would be further enhanced by including descriptions on interactive feedback between Antarctic sea-ice and other Earth system components and a discussion on the role of paleo studies in the improvement of our knowledge about the Earth system.

[Major issues]

1. Each section is poorly structured.

In each of the main sections, descriptions based on varying methodology (e.g. theory, modelling, modern observation, and paleo evidence) appear in a semi-random way, and besides, they have different structures (e.g. some sections have subsections, but others not). Therefore, it would be troublesome for readers to grasp the contents smoothly. To clarify the contributions from different methodologies, I would suggest several ideas for improvement.

- It would be helpful that each section has a table that summarizes the survey corresponding to the section. The potential table would have a similar structure to that of current Table 1; namely, columns for hypotheses based on theory and/or modelling, modern observation, paleo evidence, and so on. Then, rows would be allotted to important processes (rather than sub-components) that are relevant to the section topic.

We appreciate this suggestion, but have opted not to include a table in each section. In fact, following advice from reviewer 2, we have decided to remove Table 1 entirely. As

noted by reviewer 2, the table format tends to overly simplify and reduce the content and, as such, doesn't add much to the text. However, we have endeavoured to add clarity and uniformity to the sections by introducing a common structure and adding conceptual diagrams in each section, as explained below.

- All the main sections should have a common subsection structure. The structure might be in line with the section's table that is suggested above.

This is a great suggestion, which we have implemented. Each main section starts with an overview of the processes at play, drawing on theory, modelling and modern observations, and including a conceptual diagram. This is followed by a sub-section (with heading) on paleo insights, and finally a sub-section on knowledge gaps. For example, for section 2, this looks like:

2. Sea ice and the Southern Ocean overturning circulation

2.1 Southern Ocean overturning circulation: Overview of processes and link to sea ice

2.2. Paleo insights into sea ice and the Southern Ocean overturning circulation

2.3. Knowledge gaps: Sea ice and the Southern Ocean overturning circulation

- I would point out that the current manuscript only has insufficient visualization. I believe it will be certainly beneficial if the manuscript has more schematic illustrations that show not only the name of components but also key mechanisms or processes discussed in the main text. Fig.1 of Lannuzel et al. (2020) might be a good example of such a schematic.

We have added 3 new conceptual figures:

1. Sea ice and glacial ice (Fig 5), to accompany section 3
2. Sea ice and atmospheric circulation (Fig 6), to accompany section 4
3. Sea ice and biogeochemistry (Fig 7), to accompany sections 5 and 6

2. Table 1 should be updated accordingly.

I would suggest that the general summary should have more visualized expression that conveys the information in a more intuitive way. For example, direction of changes, correlation strength, uncertainty/reliability, and so forth would be depicted as symbols with different sizes, colors, thickness, etc. An example of such an illustration might be found in Table 1 of Henson et al. (2022; <https://doi.org/10.1038/s41561-022-00927-0>).

Apart from this, Table 1 also raises some conceptual concerns (see item #5).

We appreciate this suggestion, and we also like the table in Henson et al. 2022, but after considering it further and considering reviewer 2's comments, we prefer to remove Table 1 completely.

3. The manuscript contains a huge number of acronyms.

I would suggest that the authors should show a list of the acronyms that are used in the text.

We have added a list of acronyms and also removed 12 acronyms from the text

4. "Antarctic sea-ice as drivers of substantial Earth system changes." (Lines 113-115)

As represented by this sentence, the authors' only discuss "one-way" influences of Antarctic sea ice on other components of the Earth system. However, the relationship between the sea ice and other components should be interactive: what determines the sea-ice extent? or which controls which? In other words, not only a correlation between them but also their causal relationship should be discussed, which may be based on theoretical inferences and/or fact-based (e.g. timing analyses) discussion.

It's true that we made a deliberate decision to focus the review on the "one-way" influence of sea ice on other components of the Earth system, rather than discuss what controls sea ice extent. This was done to keep the scope manageable. However, we agree that this is somewhat artificial and we acknowledge that sea ice production and extent is in part determined by circulation, winds, and continental ice melt. We have discussed this explicitly in section 3, in the context of glacial melt and sea ice production. We have added a statement clarifying this decision at the end of the introduction:

Second, we recognize that feedbacks between sea ice and Earth system components occur in both directions. For example, while sea ice influences deep water production, ocean circulation also affects where and how much sea ice forms (Marshall and Speer 2012). While admittedly somewhat artificial, we have chosen to approach sea-ice feedbacks primarily from the perspective of how sea ice influences the Earth system, simply to make the scope of this review paper manageable.

We have also added a sentence about this in the final paragraph:

Modelling studies, particularly when pair with high-quality observational constraints, can help illuminate the nature of the two-way feedback between sea ice and other aspects of the earth system, by systematically enabling and disabling feedback processes.

5. What is the significance of paleo studies?

In some rows of Table.1, especially in the Atmosphere row, (some of) the paleo observations are treated as counter evidence, rather than positive proof. What is the background "philosophy" of this manuscript that gives more weight to other methodologies, although it is defined as "perspectives informed by 130,000 years of sea ice records"? Of course, it is well known that extracting meaningful signals from paleo indicators is not always straightforward, and that non-negligible uncertainty often

arises in their interpretation. In a general sense, when reconstructions from paleoenvironmental research conflict with understandings based on other methods, what criteria should be used to judge, and how should we move on? If this manuscript handle and discuss this fundamental issue, it will make a major contribution to research communities.

Thank you for this important comment, which touches on something we have grappled with in writing this manuscript. Our intention wasn't to give more weight to one form of evidence or the other, but we can see how Table 1 can give this impression. We see this as more reason to remove Table 1. Our 'philosophy' is to take the view of a scientist studying the Southern Ocean and Antarctica today, and wondering how declining sea ice might impact the wider system. What are the processes at play? When there are competing processes, for example for CO₂, increased sea ice leads to suppression of air-sea gas exchange as well as suppression of biological uptake of CO₂ - which process dominates? As the reviewer mentions, turning to the paleo record is not straightforward, primarily because it's difficult to isolate a single driver like sea ice when looking at any historical record. Even in the best-case scenario, this will rely on analysis of leads-lags, comparison of subtle differences between past climate states, and potentially spatial patterns. However, by revealing what actually occurred, the paleo records can provide useful additional context to other methodologies like modelling. Our intention with this review is to highlight instances where paleo observations shed some light on a) the observed relationship between sea ice and other Antarctic and SO processes and, if possible, b) the causal relationship. At this point, we probably don't have the temporal, spatial, or process level resolution in the paleo records (of both sea ice and other components) to really capitalise on this philosophy, but we think there is value in presenting this approach, taking it as far as we can, and outlining both the inherent limitations and the present limitations that could be overcome with better records. We have elaborated these points in the introduction:

L186: Our philosophy in presenting this review rests on two main points. First, we recognise that paleoceanographic reconstructions inherently involve uncertainty: interpretations do not always agree with one another or with our current understanding of physical or biogeochemical processes. While potentially challenging, this uncertainty also provides an opportunity to critically examine our understanding from the perspective of a time period with different boundary conditions. In some cases, this requires a re-examination of specific paleo-proxies; in others, allows us to test the robustness of modern interpretations. Paleo-perspectives have, for example, previously improved our understanding of abrupt climate change (e.g. Alley, 2000), the Atlantic Meridional Overturning Circulation (e.g. Broecker, 1991), and sea level (e.g. Berends et al., 2021). Second, we recognize that feedbacks between sea ice and Earth system components operate in both directions. For example, while sea ice influences the Southern Ocean upper and lower overturning cells, ocean circulation also affects where and how much sea ice forms (e.g. Marshall and Speer 2012). Although this framing is somewhat artificial, we primarily approach sea-ice feedbacks primarily from the perspective of how sea ice influences the Earth system, simply keep the scope of this review manageable.

6. Section 5.2: dimethyl sulphide

It seems to be somewhat peculiar that the authors suddenly start a topic about a particular chemical compound, although they deal with large components or subsystems in the Earth system in other (sub)sections. Is there any particular reasons for that? Otherwise, the section 5.2 would look anomalous.

We have reorganised section 5, renaming it **Sea ice and Southern Ocean biogeochemistry**. This section starts with a “zone by zone” overview of processes, starting from the sea-ice impacted zones and moving north. We now include the discussion of DMS as a process occurring within the sea ice zone. We discuss the ice core DMS records themselves in the “paleo insights” section (5.2). This removes dimethyl sulphide (previously section 5.2) as a stand-alone section.

[A comparatively minor issue]

- L.68 regime shift

What exactly does this "regime" indicate? Do we find any evidence or trace of a similar regime shift in the paleo-record? If yes, descriptions about recorded shifts should be added. If not, the reasons why such a shift is not recorded in the history of large-scale climate changes.

This is an interesting question. The regime shift described in the Hobbs et al. paper describes an abrupt and ‘permanent’ decline to a new regime of decreased Antarctic sea-ice extent. This assessment was made based on statistical analysis of sea ice extent observations. A similar regime shift is not readily apparent in the paleo record, because most of the records are relatively low temporal resolution and capture glacial-interglacial changes but not interannual or even decadal changes. As such, they show continuously changing sea ice extents that respond to evolving global climate. Because regime shifts cannot be identified in the records that are the focus of this review, we have decided to remove mention of this term from the introduction.

Reviewer 2

Thank you for the very helpful feedback on our manuscript, which will strengthen the review. In particular we appreciate the careful reading of the text and suggestions on where more depth is needed. Below we provide responses to the individual comments.

Review: Chase et al. “The role of Antarctic sea ice in the Earth system: Perspectives informed by 130,000 years of sea ice records”

This paper is an interesting summary of how Antarctic sea-ice has interacted with several components of the climate system in the last glacial cycle, and would be potentially a very useful contribution to CP. I particularly like that it covers such a broad range of processes, and that these are brought together at various points. To me this wide scope is also the main weakness – I have come away with the view that most

sections seem a little superficial / lacking depth – this paper covers so much ground (or, rather, water!) that I think it needs to be considerably longer to do justice to a very substantial body of past work. In particular, the need to review modern processes to provide context for paleo studies, means that the modern part is lacking detail and the paleo examples are perhaps too few or lacking sufficient discussion of their important nuances (especially uncertainties / limitations). More figures are also needed – both schematics showing processes/feedbacks, and also to show results of key studies that are discussed in more depth.

RESPONSE: We thank the reviewer for these insightful and constructive comments. We have added 3 new conceptual figures:

1. Sea ice and glacial ice (Fig 5), to accompany section 3
2. Sea ice and atmospheric circulation (Fig 6), to accompany section 4
3. Sea ice and biogeochemistry (Fig 7), to accompany sections 5 and 6

We also appreciate the comment about the scope. We are wary of increasing the length significantly, but we agree there is scope to add depth to all of the sections, and in particular to discuss the paleo examples more completely. We feel the restructuring of the sections, with dedicated sub-sections on 'overview of processes', 'paleo insights' and 'knowledge gaps' will increase the depth while keeping the length manageable.

Some more specific comments follow.

L91 “Sea-ice presence along the Antarctic coast buttresses ice shelves, stabilising the ice shelf and associated glaciers (Christie et al., 2022).”

Whether or not sea-ice can buttress an ice shelf is still uncertain & under debate. For just one example see Surawy-Stepney et al. (2024) who found negligible buttressing of Larsen B by sea-ice.

Please revise to present a more balanced view.

RESPONSE: We thank the reviewer for calling our attention to Surawy-Stepney et al. (2024), which presents greater complexity of the relationship between sea ice, ice shelves and glacier dynamics, with their modelling work supporting the secondary contribution of landfast sea ice in impacting ice shelves. We have re-written this statement and, then, section 3.1 to reflect this. We also included additional references that are part of this ongoing discussion, including Ochwat et al. (2024) and Sun et al. (2023). We also have re-worded this in accordance with the details explained in Surawy-Stepney et al. (2024), who distinguish “buttressing” mechanisms versus “non-buttressing mechanisms” the landfast sea ice can have on ice shelves.

L113: subheading here? Since the subsequent text suddenly dives from a general discussion into more detailed discussion of LIG sea ice and SST.

RESPONSE: We've opted not to add a subheading, but have made the subsequent section less detailed as suggested

L122-128 explanation of marine isotope stages & glacial cycles: seems unnecessary for CP.

RESPONSE: We agree and have removed it

L129 "Sea salt sodium measurements in ice cores". Only one ice core (EDC) is implied in Fig 2c. Are there some others to include?

RESPONSE: These are indeed only from EDC, so we have deleted "in ice cores" in this sentence

L137-140. Ranges of LIG SST: what are they? Are these the ranges between different studies?

RESPONSE: These are ranges based on previous studies that have been published in Gao et al. (2025). We have clarified this in the text on Line 142. As explained below, we have also reorganised this paragraph to treat the LGM and LIG in the same way, detailing both sea ice and SST changes.

South of 40°S, annual mean reconstructed SSTs were 2.2 to 2.7°C warmer than the pre-industrial temperatures, while average summer SSTs were 1.2 to 2.2°C higher than the preindustrial period, depending on the reconstruction (Gao et al., 2025)

Fig 2. The small text on the map is hard to read, so a legend would be helpful for the different sea-ice extents.

RESPONSE: We have added a legend. We have also removed the SAF from this figure to remove some clutter and changed the symbols used to plot the sea ice compilation cores. Finally, we have updated the core locations to match those now plotted in figure 4.

L160 I think the detail in this paragraph is not really justified by the uncertainties. To me it's only really the Scotia sector that stands out as responding differently, in Chadwick et al. 2022 Fig 4.

RESPONSE: We have removed most of this detail

L174 Now we're back to a general view and paper objectives. Should this be moved to before L113? Or move the material in Lines 113 to 173 to dedicated sections later on.

RESPONSE: We prefer to keep the paper objectives at the end of the introduction. We have instead greatly simplified the material that had been in Lines 113-173, summarising sea-ice changes during glacial-interglacial cycles to more clearly summarise: a) methods of reconstructing sea ice, b) a summary of LGM reconstructions including SST, c) a summary of LIG reconstructions, including SST, d) a

broad overview of timing across the glacial cycle, and e) limitations of proxy datasets. These paragraphs appear on lines 111 - 147 of the revised manuscript.

L196 Bathymetry might play a role in addition to Ekman divergence. See Tamsitt et al. 2017

RESPONSE: Thank you for this reference, we have added this to the sentence.

L210: Ekman divergence driven by the Southern Hemisphere westerlies, in interaction with topography (Tamsitt et al., 2017), causes CDW to upwell to the surface, where it splits into southern and northern branches (Fig. 3; Rintoul et al., 2001).

L236 Nice comparison with warming scenarios, but if you're wanting to compare with a warming scenario, it might be better to pick more than one study. What do the CMIP6 models predict?

RESPONSE: This is a good point. The Li et al. (2021) conclusion about warming scenarios is actually based on the ensemble mean of CMIP5 models while Almeida et al. (2024) look at the response of AAIW in CMIP6 models. They find a reduction in AAIW production in the warming scenarios. We will add this reference. In the revision, we have clarified both points.

L231:

Interestingly, Li et al. (2021) found that in Coupled Model Intercomparison Project 5 (CMIP5) models, AAIW also shoals under a global warming scenario owing to increasing temperature and decreasing density, despite a southward shift in the latitude of subduction. In their analysis of CMIP6 models, Almeida et al. (2024) found that the formation and northward transport of AAIW decrease under warming scenarios, although the formation regions remain unchanged relative to historical runs. Overall, important challenges remain in understanding the processes governing the formation of intermediate and mode waters and in representing them accurately in climate models.

*Almeida, L., Mazloff, M.R., Mata, M.M., 2024. The Influence of Surface Fluxes on Export of Southern Ocean Intermediate and Mode Water in Coupled Climate Models. Journal of Geophysical Research: Oceans 129, e2024JC021841.
<https://doi.org/10.1029/2024JC021841>*

L244 / Fig 4c. The %AAIW reconstruction seems to be very noisy, and so not very convincing. Unless you can show the uncertainties are tiny, I suggest not to include this record & related discussion.

RESPONSE: We agree that the reconstruction shown in Fig 4c is noisy, and we have removed this from the figure. However, we have opted to retain the related discussion, as this is a review paper, and multiple authors have discussed evidence for a shoaling of AAIW in the Atlantic sector during glacial periods.

L281: Puzzle of where AABW formed in LGM. If we suppose dense water from brine rejection sinks to the seafloor, does it really matter whether it formed on the shelf or in

the open ocean during the LGM? The end result would still be the same, i.e., more AABW filling the abyssal Southern Ocean?

RESPONSE: This is a good point that we now discuss. Most models form AABW in the open ocean, so in ‘model world’ such a shift is inconsequential, but the impact in the real ocean can only be guessed. We added this text on line 324:

More broadly, polynyas at the continental shelf edge may have allowed brine production and deep-water formation to occur over the continental slope during the LGM. Gordon (2014) suggests the northward expansion of the Antarctic air mass during the LGM may have blocked precipitation from mid-latitude storms (analogous to the negative Southern Annular Mode (SAM)), thereby producing slightly saltier surface water. This could have weakened stratification and enabled deep water convection driven by heat loss, analogous to the large winter-long Weddell Sea polynyas of the mid 1970s. Most global-scale ocean climate models do not have the resolution, or representation of sea ice and glacial ice processes, required to accurately form AABW through Dense Shelf Water formation on the shelf (Aguilar et al., 2025). Instead, AABW formation is typically represented as an open ocean process, similar to that associated with the Weddell Sea polynyas of the mid 1970s. This makes it difficult to assess the implications of changes in the mode or location of AABW production, or to determine what proxy signature would be expected from different modes of AABW formation.

L286: Foram deposits could presumably represent short episodes with polynyas, they don’t have to be continuous?

RESPONSE: We have reworded this as we didn’t mean to imply that the polynyas were continuously present, just that they continued to be present even during the much colder conditions of the LGM.

L318: Additionally, Smith et al. (2010) interpret benthic and planktonic foraminiferal deposits in the northwest Weddell Sea as evidence for the intermittent presence of a polynya during the LGM, and suggest polynyas were widespread around Antarctica at that time, including in the Ross Sea, SE Weddell, and Dronning Maud Land. In the latter region, the presence of polynyas during the LGM is supported by analyses of snow petrel deposits on land (McClymont et al., 2022), although it remains difficult to determine whether this reflect shelf or slope environments.

L302 “Weakening of NADW” do you mean weakening of NADW production, or export, or somehow weakening of its physical properties?

RESPONSE: We mean weakening of its production and have clarified this sentence.

L345: Model-data comparisons and inversion studies suggest the LGM Atlantic water mass geometry resulted from a shoaling of NADW during the LGM (Fig. 3; Menviel et al., 2017; Oppo et al., 2018; Pöppelmeier et al., 2023; Tagliabue et al., 2009), and likely also from a (moderate) weakening of NADW production (Blaser et al., 2025; Meissner et al., 2003; Menviel et al., 2017; Pöppelmeier et al., 2023).

L335 “This unexpected behaviour... “ I’m not convinced that this study alone (Shub et al. 2024) from the Brazil margin in TII is itself sufficient to question a direct link between sea-ice production/extent and AABW volume.

RESPONSE: We agree that the result is surprising and it’s unexpected that the boundary shoaled during MIS5e, but the result is difficult to explain away. We do agree that more evidence is required to really question the link between sea-ice production and AABW volume. We have therefore modified the last sentence of this paragraph on Line 382:

If the Brazil Margin results can be confirmed at other locations, this would imply the link between sea-ice extent and AABW volume is more complex than previously assumed.

L365 / Section 3.1 (Sea ice as a buffer for ice shelves). As noted above (L91) I think this issue is still debated in the glaciology community. This section should be expanded considerably to reflect other opinions, or perhaps omitted.

RESPONSE: As noted above, we thank the reviewer for calling our attention to Surawy-Stepney et al. (2024), which presents greater complexity of the relationship between sea ice, ice shelves and glacier dynamics, with their modelling work supporting the secondary contribution of landfast sea ice in buttressing ice shelves. We have re-written all of section 3.1 to reflect this, and include additional references that are part of this ongoing discussion, including Ochwat et al. (2024) and Sun et al. (2023). We also have re-worded this in accordance with details explained in Surawy-Stepney et al. (2024) who distinguish “buttressing” mechanisms versus “non-buttressing mechanisms” as related to the secondary impact the landfast sea ice can have on ice shelves.

While this topic is more complex than originally presented here, we feel it is important, so our preference is to retain this edited, expanded, and more complete presentation.

L398 “Increased stratification is also observed at the Totten Glacier...” Increased when and relative to what?

RESPONSE: This has been removed in our restructuring of this section

L418 “... during glacial climates when grounded ice expanded across the continental shelves

419 around Antarctica...” It’s really not certain that the ice sheet advanced to the shelf edge everywhere. See the Bentley paper you’ve cited, or Klages et al. 2017.

RESPONSE: Thank you - we’ve edited this sentence to more specifically note that glacial ice did not advance to the shelf edge everywhere around the continental margin, and added the reference to Klages et al. (2017).

L428, attributing sea-ice increase to greater ice sheet melt. This logic might have sounded reasonable prior to 2016, and indeed motivated a whole suite of hosing

studies. But the ice sheet melting hasn't slowed down as far as we know, yet the Antarctic sea ice is now at its lowest extent – so this argument is now seeming weaker.

RESPONSE: This has been removed in our restructuring of this section

L431-437 These are common features across many other studies too. See Swart et al. 2023 & refs therein. Or, Chen et al. 2023 for an ensemble view.

RESPONSE: Please see comments below.

L446-449, Subduction of water that has been heated by insolation: this was already covered earlier (L414 approx) but different references are cited.

RESPONSE: Thank you. We have re-organized section 3.2 to minimize redundancy. We think this re-organizing provides a more streamlined text.

L442-444, L456-456: first it's stated that increasing stratification can allow warmer CDW to access ice shelf cavities, then it's later stated that increasing stratification prevents CDW mixing onto continental shelves. This seems contradictory, and overall I found this section (3.3) is struggling to summarise concisely a large body of research on the environmental drivers of ice shelf basal melt.

RESPONSE: As noted in the comment above, we have re-organized section 3.2. The reviewer is correct that we mis-stated the relationship between stratification and CDW access to ice shelf cavities in lines 455-456. This has been fixed.

L485-487 "This process may also have occurred westward in Prydz Bay where a similar sea-ice increase was observed". Due to increasing super-cooled ice shelf water from where? Also not sure where do you mean by "Westward in Prydz Bay", are you meaning west of Wilkes Land?

RESPONSE: Thank you, we've deleted this sentence and the reference Denis et al. (2010). The paper does report a decrease in sea ice in their Prydz Bay core but does not attribute this to super-cooled ice shelf water.

L497-L499, use past tense here.

RESPONSE: Thank you, the use of past tense has been incorporated.

L512. An increase in IRD at one site could have many different interpretations that are not necessarily indicative of ice sheet retreat. Certainly the next sentence ("This sequence of events supports the link between sea ice as a buffer for ice shelves and the potential role of decreased sea-ice cover in facilitating basal melt and ice shelf disintegration") isn't justified by the evidence presented here. If sea-ice provided zero buttressing to ice shelves, you would still probably end up with a time series very similar to Fig 5.

RESPONSE: This is a good point. We have opted to remove figure 5 entirely and have modified the paragraph to acknowledge the ambiguity of IRD records.

L555: While the preceding examples provide evidence of sea ice responding to changes in the ice sheet and ice shelves, there is little evidence in the paleo record for sea ice influencing glacial ice. One potential example is the relative timing of sea ice decrease and ice-rafted debris increase during the last deglacial transition in the Adelie Land region of the Wilkes Land margin shelf (Pesjak et al., 2023). Here, as the climate warmed, sea-ice cover began to decrease before an increase in ice-rafted debris. If the increase in ice rafted debris is interpreted as an acceleration of ice sheet retreat, this sequence of events is at least consistent with a role for decreased sea-ice cover in facilitating ice shelf disintegration, although other interpretations are possible.

L537 Should salinity be in this list of drivers?

RESPONSE: We have edited this to implicate oceanic conditions in general:

L603 While sea-ice formation, transport, and melt are driven by ocean and atmospheric conditions, the presence of sea ice also affects the state of the ocean (section 2) and atmosphere (this section)

L562 Why are ghost flux experiments the most compelling approach?

RESPONSE: The ghost flux experiments allow the ‘downstream’ impacts of sea-ice loss to be studied by introducing an additional heat flux to the sea-ice module of a climate model. In this way, they can isolate the effect of sea-ice changes. However, the method does have limitations and was shown to overestimate heating associated with Arctic sea-ice loss (England et al. 2022). In the revised version, we explain the ghost flux method and point out its advantages as well as its limitations, rather than call it the most compelling method.

L643: A modelling framework known as “ghost flux” experiments has been used to infer a causal relationship between sea-ice variability and climate. The ghost flux experiments allow the ‘downstream’ impacts of sea-ice loss to be studied, by introducing an additional heat flux to the sea-ice module of a climate model, thereby isolating the effects caused by sea-ice changes (Deser et al., 2015). However, the method does have limitations and was shown to overestimate heating associated with Arctic sea-ice loss (England et al. 2022).

England, M.R., Eisenman, I., Wagner, T.J.W., 2022. Spurious Climate Impacts in Coupled Sea Ice Loss Simulations. *Journal of Climate* 35, 7401–7411. <https://doi.org/10.1175/JCLI-D-21-0647.1>

L583 “... did nothing”. Probably it did something, do you mean “had a negligible impact” or “not statistically significant” or etc.

RESPONSE: Thank you, we have changed to “had a negligible impact on”

L666

L613 “However, recent proxy records suggest the sea-ice effect on the SHW is of second Order.” That’s not supported by a following sentence “They [Kohlfeld2013] concluded that making inferences about wind shifts based on paleo-evidence alone is difficult, as the data are consistent with multiple scenarios.”

RESPONSE: Thank you for pointing this out. We can see how it is confusing. The sentence about ‘second order’ refers to the work by Gray et al. (2023), which appears later in the paragraph. We split this into two paragraphs and rewrote it to eliminate the apparent contradictory sentences.

L695 Reliable paleo reconstructions of atmospheric attributes such as winds and precipitation are challenging to produce (Huiskamp and McGregor, 2021; Kohfeld et al., 2013; Shulmeister et al., 2004). On glacial-interglacial timescales, Kohfeld et al. (2013) compiled environmental reconstructions in the Southern Hemisphere that could plausibly be affected by a change in the SHW (e.g., moisture, dust, SST). They concluded that making inferences about wind shifts based on paleo-evidence alone is difficult, as the data are consistent with multiple scenarios. Kohfeld et al. (2013) found that a scenario with either stronger winds or an equatorward shift of the SHW during the LGM is consistent with most observations, but cautioned that no change, or even a poleward shift, could not be ruled out.

An alternative and more recent proxy approach to reconstructing SHW suggests direct impact of sea ice on the SHW is of second order (Gray et al., 2023). This work inferred a poleward shift of the SHW during the last deglaciation from the latitude of the steepest SST gradient in the Southern Ocean, which they reconstructed from a compilation of planktonic $\delta^{18}\text{O}$ measurements. Gray et al. (2023)’s reconstruction is consistent with the predicted wind direction response under future warming scenarios, but opposite in sign to the typical model-derived response to a decrease in sea ice described above. These results suggest that the decrease in sea ice during deglaciation (Crosta et al., 2022), which would on its own yield an equatorward shift in SHW, was not enough to offset the poleward tendency due to climate warming. Interestingly, the proxy-reconstructed wind shift is more than 4 degrees of latitude greater than that predicted by any of the CMIP4/3 models investigated (Gray et al., 2023). While there are many possible explanations for this discrepancy, including biases in the observational constraints, one possibility is that the sea-ice effect on SHW is too strong in the models, overcompensating for the warming-driven trend that shifts SHW poleward.

L621 “... a poleward shift of the SHW during the last deglaciation from the latitude of SST gradients in the Southern Ocean” Not sure what is meant by the latitude of an SST gradient.

RESPONSE: We have clarified this as “a poleward shift of the SHW during the deglaciation from the latitude of the steepest meridional SST gradient”

L647-650 If the ssNa signal in 5 cores examined by Buizert et al. 2018 is “weak and not observed in all cores” then how is the next statement justified (“Yet, the sign and timing of the sea-ice signal, and its relationship to the inferred wind changes, do not support a strong link between changes in sea ice and changes in atmospheric circulation over millennial timescales.” I’ve lost track of the logic here.

RESPONSE: Thank you for highlighting this. The reference to ssNa and Buizert was an error, and we can see how this whole section was confusing. We have reworded this and added further references, making it clear that the inferred sea-ice changes based

on ssNa consistently show a decrease in sea-ice extent during Antarctic warming, but not during equatorward wind shifts. This section now reads:

L720: While no ocean-based sea-ice records exist that resolve these millennial events, four ice core records show evidence of sea-ice decreases associated with millennial-scale Antarctic warming events. Both the Dronning Maud Land (Fischer et al., 2007) and the Talos Dome Ice Cores (Buiron et al., 2012) show abrupt decreases in ssNa, interpreted as a rapid decrease in sea-ice extent, at the start of each Antarctic warming event, followed by a gradual recovery as Antarctica cooled. A similar trend is seen near the Ross Ice Shelf (Venugopal et al., 2023). Finally, near the centre of West Antarctica, less ssNa during the deglaciation was indicative of decreasing sea-ice extent and increasing $\delta^{18}\text{O}$ was indicative of warming (WAIS group 2013). Conversely, using water isotopes in five Antarctic ice cores, Buizert et al. (2018) infer an equatorward shift of the SHW nearly synchronous with Northern Hemisphere warming events, rather than with Southern Hemisphere temperatures. In summary, the Antarctic sea-ice response tracked Antarctic temperature, with a decrease in extent as Antarctica warmed, while the wind response was closely tied to Northern Hemisphere warming. The abrupt equatorward shift in the winds occurred against a backdrop of increasing Antarctic sea-ice extent and was associated with abrupt Northern Hemisphere warming rather than with any notable shift in Antarctic sea-ice dynamics. Rae et al. (2018) highlight a similar dynamic during millennial variability of the last deglaciation: Antarctic ice core deuterium suggests a northward shift of the SHW coinciding with abrupt Northern Hemisphere warming (Markle et al., 2017) and preceding the Southern Hemisphere cooling and increase in Antarctic sea-ice extent by about 200 years (Buizert et al., 2015). The observed changes in sea ice and SHWs over millennial scales, thus, suggest that the expected 'sea-ice' effect on winds is a second-order process compared to other climate feedbacks associated with warming or cooling. In conclusion, the sign and timing of the reconstructed sea-ice changes, and their relationship to the inferred wind changes, do not support a strong link between changes in sea ice and changes in atmospheric circulation over millennial timescales.

L663 proxy record – should that be plural?

RESPONSE: corrected

L670 Rather than new modelling efforts, I would start by looking at the wealth of existing climate simulations to see if any pattern can be found beyond the SHW.

RESPONSE: This is a good suggestion which we have added in addition to the targeted modelling experiments. See L754

L700 Interesting that sea ice supplies iron to the ocean. Where does that iron come from originally? How does it provide a link between glaciers/sediments and the ocean (L721)? Is this iron flux greater than the flux from icebergs and subglacial melt discharge?

RESPONSE: The iron from sea ice comes both from seawater itself, as well as from nearshore suspended sediments, if the ice is formed nearshore and then transported offshore. It also comes from dust deposited onto sea ice. We have clarified this by restructuring the sentences. We have also put the sea-ice iron sources into context relative to other iron sources.

L805: *Sea ice plays an important role in the cycling of iron in the Southern Ocean. Both pack ice and fast ice are enriched in iron by about an order of magnitude above surface Southern Ocean seawater concentrations, with fast ice, formed in closer proximity to continental iron sources, including glaciers, sediments and dust, having higher concentrations than pack ice (Lannuzel et al., 2016). Sea-ice melt in spring results in a large pulse of iron being released to seawater over a short period of time (Lannuzel et al., 2008). This springtime iron release coincides with increasing light levels, warming, and a stabilised water column, triggering algal blooms in the seasonal ice zone (Sedwick and DiTullio, 1997). In their modelling study, Person et al. (2021) show that including sea-ice iron increases carbon export in the Southern Ocean by 8% relative to a control run with no sea-ice iron. On the other hand, inclusion of iron from continental ice increases carbon export by 4.5%. Interestingly, they also found an interactive effect where the sea-ice iron source exerts a greater impact on carbon export as the continental source is incorporated into sea ice, increasing its iron content.*

Person, Renaud, Martin Vancoppenolle, Olivier Aumont, and Manon Malsang.
“Continental and Sea Ice Iron Sources Fertilize the Southern Ocean in Synergy.”
Geophysical Research Letters 48, no. 23 (2021): e2021GL094761.
<https://doi.org/10.1029/2021GL094761>.

L731 “the length of the ice-free season determines the upper limit of opal burial in the underlying sediments”... not sure I follow this sentence, what is the upper limit of opal burial?

RESPONSE: L855 We have rewritten as “*Where sea ice is present for at least part of the year, the duration of the ice-free season is an important factor limiting how much opal is exported and ultimately buried in the underlying sediments*”

L758-786. There’s no discussion here about the potential contribution of changes in iceberg nutrient fluxes to past changes in Southern Ocean productivity. Should be mentioned, even if to say it’s a negligible part of the budget.

RESPONSE: This is a good point, which falls into the category of ‘influences on productivity other than sea ice’. Several studies have suggested that iron input from icebergs can promote productivity. If iceberg discharge decreases during cold climate states, this could theoretically explain or contribute to low productivity during glacial times. However, increased iron limitation during glacial times is not consistent with the nitrogen isotope data, which indicates more complete utilisation of nitrate at the time of low productivity. We have added a sentence to clarify that IRD cannot explain the existing glacial-interglacial productivity and nitrate utilisation trends.

L879: *The combination of more complete nitrate consumption and lower opal flux is inconsistent with simple light limitation, whether imposed by sea ice or by deeper mixed layer. The nitrogen isotope evidence also argues against iron limitation – for example owing to reduced iceberg discharge (Barkley et al., 2024) – as the primary driver of low glacial productivity in the Antarctic Zone.*

L833 Can you quantify what is “long term”?

RESPONSE: In reorganising this section we have decided to delete this sentence

L849-L852 This seems very speculative!

RESPONSE: True, we have deleted this sentence

L867-869. Have there been Earth system modelling studies of this process? They would provide some useful insights.

RESPONSE: Yes, Stein et al. 2020 and Khatiwala et al. 2019 describe results from two such earth system models. These are discussed in the paragraph starting on line 956. In the revision we have reorganised this section to make this distinction more clear, and have highlighted this in section 6.3, Knowledge gaps.

L1072: A major caveat is that the models that show large impacts of sea ice on overturning circulation and ocean carbon storage, including those beyond simple box models, remain highly idealised.

L911. This is an idealised experiment – but in reality would there be much upwelling under sea ice, or instead would you expect that either (1) the region of Ekman-driven upwelling would move further north, beyond the sea-ice edge, in tandem with a northwards shift in SHW, or (2) if SHW haven't moved, then the presence of sea ice reduces Ekman divergence and upwelling. Either way there's less upwelling under the ice.

RESPONSE: Thank you for raising this. It's difficult to say what would be expected 'in reality'. The idealised experiments are useful in isolating the impact of individual mechanisms. But in reality, many things change at once - e.g. winds and sea ice, temperature and the ice sheet. The work of Stein et al. (2020) explores the integrated effect of physical changes associated with orbital and greenhouse gas forcing. They find a more vigorous Southern Ocean overturning circulation during glacial climates, yet overall a decrease in the exposure of deep Southern Ocean water to the atmosphere (e.g. a decrease in 'ventilation'). They attribute this to the sea-ice capping the upwelled water and an enhanced poleward circulation, limiting the exposure time of deep water at the surface. While this is only one model, in the revised version, we discuss this result more, and also the contrast with the work of Khatiwala et al. 2019, which may be because the Khatiwala study imposed LGM sea ice on a pre-industrial circulation.

L1026: Results from more complex models show that the CO₂ response to sea-ice is not uniform. A coarse-resolution Earth System Model suggests that sea ice can substantially limit the release of CO₂ from the upwelling of CDW (Stein et al., 2020). In this study, the authors explored the integrated effect of physical changes associated with orbital and greenhouse-gas forcing. They found a more vigorous Southern Ocean overturning circulation during glacial conditions, yet an overall 10-fold decrease in the exposure of deep Southern Ocean water to the atmosphere (that is reduced 'ventilation'). They attributed this to sea ice capping the upwelled water, together with enhanced poleward circulation that shortened the residence time of deep water at the surface. The magnitude of sea-ice related carbon sequestration estimated by Stein et al. (2020) is broadly consistent with that estimated by Marzocchi and Jansen (2019) and Ferreira (2018). In contrast, Khatiwala et al. (2019) used a more complex model to isolate individual mechanisms of CO₂ change between glacial and interglacial state, and found that imposing an expanded, LGM-like sea-ice field on a pre-industrial circulation led to a slight decrease in ocean carbon uptake, in response to a

dominant effect of reduced biological carbon uptake, as also suggested by Sun and Matsumoto (2010). Together, these results suggest it is not sea ice expansion alone, but its interaction with circulation changes, that is critical for modulating Southern Ocean carbon uptake

L944 “The lag between the expansion of sea ice and the decrease in CO₂” That lag (of 3ka) is really not clear to me in Fig 4 and is the dating of the marine sea-ice records really good enough to resolve it?

RESPONSE: This point about the lag was made by Ai et al. 2020. We have annotated Fig 4 to better highlight this feature, which we agree is subtle. We also agree that the lack of an apparent lag in the marine records could well be due to dating uncertainties. In the ‘knowledge gaps’ section we have highlight the need for more and better dating of marine records across the glacial inception.

L979-L981 “While we focus here on modern studies, as well as paleo-records spanning the last glacial cycle (150 – 0 ka), processes described are also applicable to more ancient, recent, and future conditions” What is the difference, in this paper’s context, between modern and recent?

RESPONSE: Good point, we didn’t mean to imply a distinction between modern and recent, and have deleted the reference to ‘recent’ in this sentence.

L993-995 “To increase our knowledge and further improve our understanding, we need paleo-records with higher temporal resolution and better chronologic control in more areas of the Southern Ocean” I don’t think any reader of CP would disagree with that, but obviously that’s a big task... Can you help by recommending some particular regions or time periods that should be targeted? I also wonder about the chronological control – yes this is an important issue, particularly when comparing multiple sites or data vs models, but it was really skipped over in this review.

RESPONSE: Thank you for this excellent suggestion. The main region needing better covering is the Antarctic zone, while the main time periods needing more coverage are the glacial inception as well as millennial-scale variability during MIS 3. In the revised version we will highlight these aspects. We agree about the chronological control, which is needed in particular to make inferences from the relative timing of changes in sea ice and other aspects of the system- we will make this point in the body of the review and again in this concluding section. This section now reads (Line 1117):

To improve our understanding, we need paleo-records with higher temporal resolution, greater proxy integration, and better chronologic control, particularly in the Seasonal Sea Ice Zone. A focus on millennial-scale warming events and warmer-than-present interglacial periods, is particularly relevant to future projections, whereas a focus on climate transitions, such as glacial inception and deglaciation, may help distinguish drivers from responses. Better chronological alignment across archives, together with multi-proxy studies from the

same sites, will be critical for inferring the role of sea ice from the relative timing of changes in sea ice and other aspects of the Southern Ocean system.

Table 1: Not referred to anywhere in the text, and not very helpful as it over-simplifies processes that are already covered only briefly in the text. Suggest to delete it.

RESPONSE: We agree with this perspective and will remove Table 1, replacing it with a 'knowledge gaps' subsection in each major section.