

Reviewer 1

I find that quite a few sentences suffer from poor readability, mainly because they are excessively long or structurally too complex or awkward. I therefore recommend revising them to improve readability. The examples below are sentences for which I propose revisions, but they are by no means the only ones that would benefit from revision. Sections 3 and 4, in particular, require careful revision to improve clarity and readability.

Response: We addressed all of the examples and have also read through the whole manuscript with an ear to improving readability. We provide screenshots below of the changes in response to specific suggestions, showing the new line numbers.

L.49-52 "We review how ... most robust."

93 in sea ice may affect other components of the Earth system. We review how Antarctic sea ice
94 interacts with ocean and atmosphere circulation, ice sheets and ice shelves, marine
95 productivity, and the carbon cycle. We find strong evidence from theory and models that

L.78-82 "Shown ... freshened by sea-ice melt."

131 **Figure 1: Schematic overview of the role of Antarctic sea ice in the Earth system.** Shown
132 are major water masses discussed in the text: Circumpolar Deep Water (CDW), which
133 upwells due to surface wind stress; dense shelf water (DSW), which forms Antarctic Bottom
134 Water (AABW), produced through brine rejection during sea-ice production Antarctic
135 Intermediate Water (AAIW), which is freshened by sea-ice melt. Biogeochemical processes

L.101-104 "Sea-ice extent ... (Sarmiento et al., 2004)."

162 The influence of sea ice extends to the biosphere. Sea-ice extent and seasonal melt influence
163 the timing and intensity of ice-edge phytoplankton blooms (Giddy et al., 2023), as well as
164 nutrient cycling both locally (e.g., iron, Lannuzel et al. 2016) and remotely, by influencing
165 intermediate water nutrient export to low latitudes (Sarmiento et al., 2004). Sea ice also

L.197-200 "Although this ... manageable."

289 affects where and how much sea ice forms (e.g. Marshall and Speer 2012). Although this
290 framing is somewhat artificial, to keep the scope of this review manageable, here we
291 approach sea-ice feedbacks primarily from the perspective of how sea ice influences the
292 Earth system.

L.269-272 "The LGM provides ... LGM oceanic circulation."

377 The LGM provides a useful test bed for understanding the relationship between sea ice and
378 ocean circulation, owing to the northward expansion of sea-ice cover during this interval
379 (Chadwick et al., 2022a; Gersonde et al., 2005; Green et al., 2022) and the extensive proxy
380 and modelling studies of LGM oceanic circulation.

l.276-269 "The characteristics ... or bulk sediment."

401 inorganic carbon (DIC) reconstructed from benthic foraminifera and the Nd isotopic
402 composition (ϵ_{Nd}) of bottom waters reconstructed using ferro-manganese coatings extracted
403 from foraminifera, fish debris, or bulk sediment. In the southwest Pacific Ocean, evidence

l.385-387 "Regardless of ... during the LGM."

573 Regardless of whether it can be attributed to expanded sea ice, the proxy evidence
574 summarised above indicates that glacial AABW (sometimes called southern component
575 water) occupied a greater volume relative to NADW during the LGM. However, this does not

l.426-429 "A complex suite ... (Fig.5)."

622 A complex suite of interconnected processes influences the relationship between sea ice, ice
623 shelves, and ice sheets (Fig. 5). These complex relationships include the potential for sea ice
624 to enhance ice shelf stability, and in some cases promote ice shelf growth. A sea-ice barrier
625 can dampen ocean swell and wave action at the ice shelf front, thereby reducing mechanical
626 stress and providing additional protection to the ice shelf (Massom et al., 2018). Conversely,

l.429-432 "These complex relationships ... (Massom et al., 2018)"

622 A complex suite of interconnected processes influences the relationship between sea ice, ice
623 shelves, and ice sheets (Fig. 5). These complex relationships include the potential for sea ice
624 to enhance ice shelf stability, and in some cases promote ice shelf growth. A sea-ice barrier
625 can dampen ocean swell and wave action at the ice shelf front, thereby reducing mechanical
626 stress and providing additional protection to the ice shelf (Massom et al., 2018). Conversely,

l.445-448 "The disintegration ... (e.g. Miles and Bingham, 2024)."

653 The disintegration of many Antarctic ice shelves over the past several decades, resulting from
654 warm ocean currents and rising atmospheric temperatures, has attracted considerable

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659 attention because of the important role ice shelves play in buttressing glacial ice, and the
660 consequent implications for sea level rise (e.g. Miles and Bingham, 2024). Questions about

L.452-455 "Additionally, ... Stepney et al., 2024). "

664 Lauber et al., 2023; Robinson and Haskell, 1990; Teder et al., 2022, 2025). Additionally,
665 when direct buttressing is minimal, landfast sea ice may still influence glacier stability
666 indirectly by reducing wave and swell impacts on ocean-terminating glaciers, through its role
667 in bonding the "ice melange" (Sun et al., 2023; Surawy-Stepney et al., 2024). Ultimately, sea

L.475-479 "This scenario ... (Kusahara et al., 2023)."

689 et al., 2019). This mechanism has been further explored through modelling work, which

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702 suggests that extreme warming events and associated reductions in coastal sea ice can lead to
703 ice sheet mass loss. This occurs through increased intrusion of warm water across the
704 continental shelf, allowing it to penetrate beneath ice shelves and enhance basal melting
705 (Kusahara et al., 2023). Decreased sea-ice cover, and associated increase in solar heating at
706 the ocean surface, might therefore play a role in future ice shelf stability.

L.533-535 "In these locations, ... (Jourdain et al., 2017)"

168 outflow of supercooled Ice Shelf Water. This outflow cooled the downstream waters along
169 the Wilkes Land margin and facilitated the increased production of sea ice. Importantly, in

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179 smaller ice shelf cavities, such as in the Amundsen Sea, the opposite response may occur
180 today. In these locations, melting is driven by the incursion of relatively warm CDW. The
181 warming effect of this deep-water inflow exceeds the cooling influence of ice sheet
182 meltwater, leading to a warmer sub-ice shelf cavity and reduced sea-ice cover near the ice
183 shelf front (Jourdain et al., 2017).

I.544-548 "Proxy records ... spring insolation."

1792 cooling at this time, so the melt must have been driven by ocean warming. Proxy records of
1793 sub-surface ocean temperature (Etourneau et al., 2013; Kim et al., 2012; Shevenell et al.,
1794 2011) and water column mixing (Denis et al., 2010) suggest a period of enhanced CDW on
1795 the continental shelf. The resulting ice sheet melt increased freshwater input to the ocean at a
1796 time of decreasing spring insolation, which together promoted sea-ice formation. Weber et al.
1797 (2014) also modelled the impact of the Antarctic ice discharge event during the Antarctic
1798 Cold Reversal of the last deglaciation (14.8 - 14.4 ka). They found the freshwater input drove

I.583-586 "Additional spatial coverage ... in the modern ocean."

1885 involve both field-based and satellite-derived data acquisition. Additional spatial coverage
1886 examining the relationship between changes in sea ice and adjacent ice shelves, as done for
1887 the Larsen B region (Ochwat et al., 2023; Sun et al., 2023; Surawy-Stepney et al., 2024), will
1888 provide a more deeper understanding of the impact of sea ice on ice shelf stability. Fürst et

I.608-611 "Because the winter ... atmospheric circulation."

1925 1986). Since the winter sea-ice edge sits in the atmospheric polar frontal zone, a region of
1926 uplift at the boundary between the polar and midlatitude (Ferrell) cells, even minor changes
1927 in Antarctic sea-ice extent can trigger significant shifts in atmospheric circulation (Raphael et
1928 al., 2011).

l.626-630 "Note that ... in response to strong"

952 and Visbeck 2002; Purich et al. 2026). It is worth noting that the equatorward shift of the
953 SHW linked to declining sea ice is contrary to the overall model predictions for SHW
954 behaviour under climate warming. These models uniformly suggest a poleward shift of the
955 SHW as CO₂ levels increase (Goyal et al., 2021; Yin, 2005). This is because the meridional

l.643-646 "The ghost flux ... (Deser et al., 2015)."

977 A modelling framework known as "ghost flux" experiments has been used to infer a causal
978 relationship between sea-ice variability and climate. The ghost flux experiments allow
979 researchers to study the downstream impacts of sea-ice loss to be studied. This is achieved by
980 introducing an additional heat flux to the sea-ice module of a climate model, which isolates
981 the effects caused by sea-ice changes (Deser et al., 2015). However, the method does have

l.664-666 "While a 7-degree ... of the SHW."

1011 asymmetric response. While a decrease in sea-ice extent of 7 degrees latitude, in either winter
1012 or summer, had a negligible impact on the winds, an increase in sea-ice extent of 7 degrees,
1013 in winter only, caused a poleward shift of the SHW. The latter sea ice scenario is analogous

l.680-683 "However, in these simulations ... slightly poleward."

1042 westerlies in warm climates and equatorward-shifted westerlies in cold climates. However, in
1043 these simulations with a less-accurately placed modern-day sea-ice edge, the presence of
1044 expanded LGM sea ice reversed the equatorward trend in the westerlies in cooler climates.
1045 Consequently, winds in LGM simulations were more likely to have been shifted slightly
1046 poleward. Thus, accurately reconstructing LGM sea-ice extent is the key to understanding

l.685-687 "This state dependence ... climate scenarios. "

1047 LGM SHW wind changes. This state dependence may explain why, despite near uniform
1048 agreement among models that the winds will shift poleward in warming climate scenarios,
1049 there is disagreement among models about the sign and magnitude of the deglacial wind
1050 shifts. The offsetting effect of sea ice on winds, counteracting the climate warming signal,
1051 likely varies in strength across different models. This variation may lead to a wide range of

l.688-690 "It may be ... deglacial change."

1050 shifts. The offsetting effect of sea ice on winds, counteracting the climate warming signal,
1051 likely varies in strength across different models. This variation may lead to a wide range of
1052 predicted wind shifts when simulating the deglacial change. An open question is how
1053 important the sea-ice effect on the SHW is in the real climate system. The paleo record may
1054 provide clues.

L.716-718 "While there are ... shifts SHW poleward."

1089 There are many possible explanations for this discrepancy, including biases in the
1090 observational constraints. However, one possibility is that the sea-ice effect on SHW is too
1091 strong in the models, and overcompensates for the warming-driven trend that shifts SHW
1092 poleward.

L.722-725 "Both the ... Antarctica cooled."

1095 warming events. Abrupt decreases in ssNa, interpreted as a rapid decrease in sea-ice extent,
1096 are observed at the start of each Antarctic warming event in both the Dronning Maud Land
1097 (Fischer et al., 2007) and the Talos Dome Ice Cores (Buiron et al., 2012). These are followed

L.748-750 "However, ... the case is not closed."

1130 in driving SHW variability. However, this conclusion is tempered by the significant
1131 limitations of the wind proxies, the difficulty of discerning leads and lags, particularly in
1132 lower resolution marine records, and the diversity of model responses to greater than present
1133 sea-ice extent. Given the widespread teleconnections and far-field response to declining sea

L.805-809 "Both pack ice ...(Lannuzel et al., 2016). "

1193 Ocean seawater concentrations. Fast ice, formed in closer proximity to continental iron
1194 sources such as glaciers, sediments and dust, has higher iron concentrations than pack ice
1195 (Lannuzel et al., 2016). Sea-ice melt in spring results in a large pulse of iron being released to

L.815-817 "Interestingly, ... its iron content."

This sentence has been deleted

L.818-821 "Biological processes ... (Malin and Erst, 1997)."

1202 Biological processes associated with sea ice are important to the production of dimethyl
1203 sulphide (DMS), a semi-volatile sulphur compound. The oxidation of DMS produces
1204 sulphate aerosols, which act as cloud condensation nuclei and are, therefore, important in
1205 regulating precipitation and albedo (Charlson et al., 1987). DMS is produced in ocean surface

l.937-941 "Longer reconstructions ... productivity."

1348 are needed to better identify the biological response to sea-ice changes. Reconstructions of
1349 biogenic sulphur emissions (Fischer et al. 2025) across multiple glacial cycles will also help
1350 clarify the link among climate, sea ice, and DMS and help resolve the disagreement between
1351 ice-core- and sediment-core-based reconstructions of Antarctic Zone productivity.

l.1037-1041 "In contrast, ... Sun and Matsumoto (2010)."

1484 Jansen (2019) and Ferreira (2018). In contrast, Khawiwala et al. (2019) used a more complex
1485 model to isolate individual mechanisms of driving CO₂ changes between glacial and
1486 interglacial states. They found that imposing an expanded, LGM-like sea-ice field on a pre-
1487 industrial circulation resulted in a slight *decrease* in ocean carbon uptake. This was primarily
1488 due to a strong reduction in biological carbon uptake, as also suggested by Sun and
1489 Matsumoto (2010). Together, these results suggest it is not sea ice expansion alone, but its
1490 interaction with circulation changes, that is critical for modulating Southern Ocean carbon
1491 uptake.

For example, taking the sentence on l.688, one possible revision is shown below.

"It may be that the offsetting effect of sea ice on winds, acting in opposition to the climate warming signal, operates at different strengths in the various models, resulting in a wide range of predicted wind shifts when simulating the deglacial change."

-> "The offsetting effect of sea ice on winds, acting in opposition to the climate warming signal, may differ in strength across models. This variability could explain the wide spread in simulated deglacial wind shifts."

Splitting it into two sentences improves readability and, as a result, makes the overall text shorter.

Similarly, l.716 would be:

"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."

-> "Several factors could account for this discrepancy, including biases in the observational constraints. One possibility is that models overestimate the influence of sea ice on SHW, which overcompensates the warming-driven tendency for SHW to shift poleward."

[other minor issues]

- The following words should be included in the abbreviation table.

PE (shown in Fig.1)

ssNa

SIE (shown in Fig.2)

SAM

PFZ

SSIZ

Acronym	Meaning
AABW	Antarctic Bottom Water
AAIW	Antarctic Intermediate Water
APF	Antarctic Polar Front
CDW	Circumpolar Deep Water
CMIP	Coupled Model Intercomparison Project
C-SIDE	Cycles of Sea Ice Dynamics in the Earth system
DIC	Dissolved Inorganic Carbon
DMS	Dimethyl Sulphide
DMSP	<u>Dimethylsulphoniopropionate</u>
DSW	Dense Shelf Water
EPICA	European Project for Ice Coring in Antarctica
LGM	Last Glacial Maximum
MIS	Marine Isotope Stage
NADW	North Atlantic Deep Water
PAGES	Past Global Changes
<u>PE</u>	<u>Polar Easterlies</u>
<u>PFZ</u>	<u>Polar Frontal Zone</u>
PMIP	Paleoclimate Modelling Intercomparison Project
POOZ	Permanently Open Ocean Zone
SAZ	Subantarctic Zone
SAF	Subantarctic Front
<u>SAM</u>	<u>Southern Annular Mode</u>
SAMW	Subantarctic Mode Water
SHW	Southern Hemisphere Westerlies
<u>SIE</u>	<u>Sea-Ice Extent</u>
<u>ssNa</u>	<u>Sea Salt Sodium</u>
<u>SSIZ</u>	<u>Seasonal Sea Ice Zone</u>

- I.143

Does "average summer SSTs" mean global-mean summer SSTs?

No, only south of 40S. We have deleted 'average' to remove this ambiguity

- The title of section 2

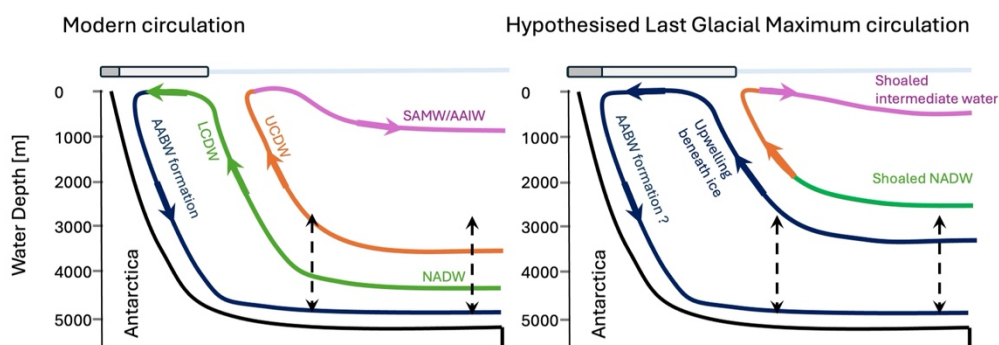
Section 2 actually devotes a substantial amount of discussion not only to ocean circulation but also to water mass configuration. I therefore suggest revising the section title so that it more accurately reflects its content.

The title has been changed to "Sea Ice and Southern Ocean water masses and circulation"

- Fig.3

Between the two illustrations, the roles of the orange and green lines are opposite.

Thank you for pointing this out. We have edited the colours to make it clear that the LGM circulation is two closed cells, rather than a figure 8. We also adjusted the sea ice lid width and indicated summer and winter ice.



- L.428

Fig.5 is referred to in the main text earlier (L.428) than Fig.4 (L.515), which might not be reasonable.

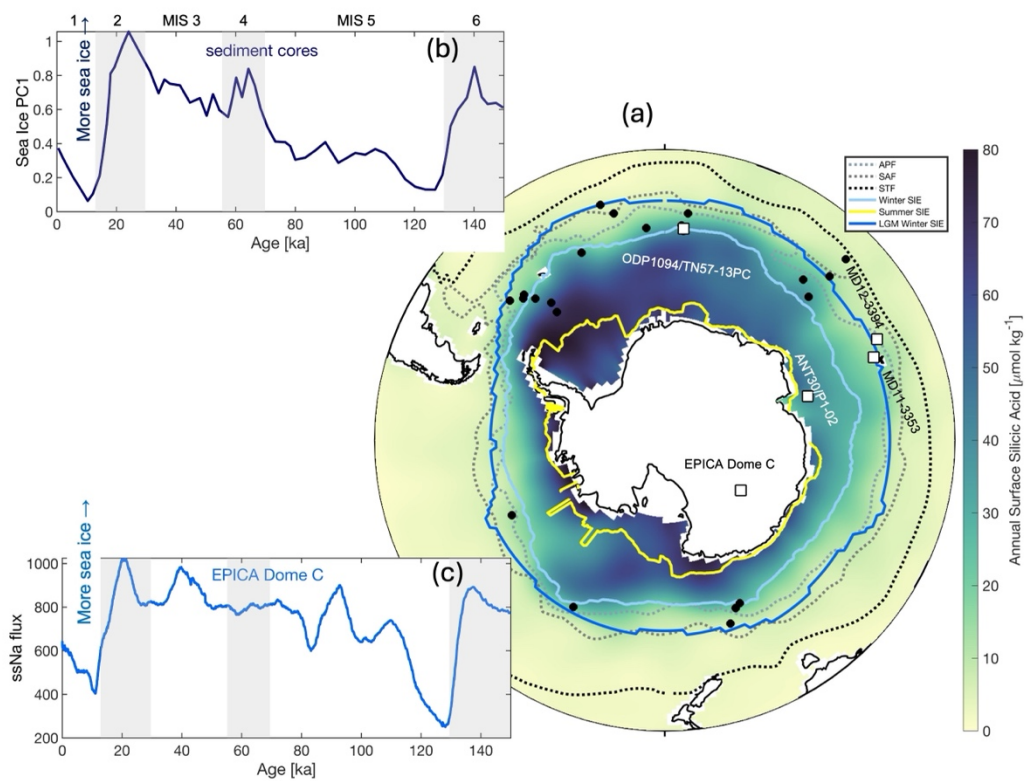
Thank you for catching this. We have added a reference to figure 4 in the final paragraph of section 2.2, before reference to figure 5.

- L.774: the Southern Ocean is comprised of five zones ... (see Fig.2)

Actually, only some of the five zones are shown in Fig.2. It would be better to visualize all of them (in Fig.2 or in a separate figure).

We have added the Subtropical Front and the Subantarctic Front to Figure 2. In this way the 5 zones can be identified based on their descriptions, but we have not labelled

them on Figure 2 as it is already very crowded.



- l.978

reductio -> reduction fixed

- l.1093

The second "and" should be deleted. fixed

- l.1121

The comma after "periods" should be deleted. fixed

Reviewer 2

L44: add connecting word between the two parts of the sentence, or split, e.g. "Antarctic sea ice is closely linked to multiple components of the Earth system, *consequently* its demise could precipitate ..."

Added 'As' to the start of the sentence

L52 "... for sea-ice reconstructions are most robust" Does this last part of the sentence need rephrasing?

We deleted the last part of the sentence, as it seemed unnecessary for the abstract. It now reads "We review how Antarctic sea ice interacts with ocean and atmosphere circulation, ice sheets and ice shelves, marine productivity, and the carbon cycle."

L78 Add some punctuation apart from commas to clarify this sentence. For example "Shown are major water masses discussed in the text, including dense shelf water (DSW), which forms Antarctic Bottom Water (AABW), produced through brine rejection during sea-ice production; Circumpolar Deep Water (CDW), upwelling due to surface wind stress; and Antarctic Intermediate Water (AAIW), freshened by sea-ice melt."

131 **Figure 1: Schematic overview of the role of Antarctic sea ice in the Earth system. Shown**
132 are major water masses discussed in the text: Circumpolar Deep Water (CDW), which
133 upwells due to surface wind stress; dense shelf water (DSW), which forms Antarctic Bottom
134 Water (AABW), produced through brine rejection during sea-ice production Antarctic
135 Intermediate Water (AAIW), which is freshened by sea-ice melt. Biogeochemical processes

L85 Katabatic doesn't need capital letter? changed

L107 Replace "strongly" with "strong". Deleted 'has' to correct grammar: "Through these physical and biogeochemical processes, sea ice strongly influences ocean carbon uptake and the global carbon cycle"

L198 "primarily" use twice, can delete one. done

L199 Replace "simply" with "to".

We have rewritten this sentence: "Although this framing is somewhat artificial, to keep the scope of this review manageable here we approach sea-ice feedbacks primarily from the perspective of how sea ice influences the Earth system"

L209 "Bathymetry" might be better than "topography" changed

L428 "... ice shelves - the floating extension of glacial ice, and ice sheets - grounded at their base to the underlying bedrock or its sediment cover ..." better written as "... ice shelves - the floating extensions of the grounded Antarctic Ice Sheet ..."?

We have deleted these explanations from this sentence and instead added them to the caption for figure 5: "Figure 5: Schematic representation of the Antarctic ice sheet, grounded to the underlying bedrock or sediment cover, ice shelves, the extension of glacial ice, and adjacent ocean processes."

L542, Drivers of increasing ice shelf melt (ocean, rather than air temp) during the Holocene. This argument is well supported by other recent work, and neatly connects deep ocean changes with sea ice changes.

First the air vs ocean temp control on ice shelf melt - there's not much surface melting of ice shelves at present, and a lot of atmospheric warming is needed to reach a substantial contribution from surface melting, so it's the basal melting that dominates the local melt fluxes under modern-like or slightly warmer climates (see Coulon et al. 2024, 10.1029/2024GL111250). Changes in (deep) ocean temperature - rather than air temperature - are the main control on changes in shelf melt, both in recent decades

(Schmidtke et al. 2014, 10.1126/science.1256117, or more recent refs) and over glacial cycle timescales (e.g. Clark et al. 2020, 10.1038/s41586-020-1931-7; Chandler et al. 2025, 10.1038/s43247-025-02366-2).

Second the feedback between ice shelf melt and ocean surface changes is alluded to later (L551), but as a topic of much recent interest it could be briefly introduced at the start of Section 3? Deep ocean warms and drives increasing melt, then the resulting increase in freshwater export near the surface in turn impacts sea ice formation (for an idealised model ensemble specifically testing that, see Mulwijk et al. 2026 10.5194/tc-20-1087-2026, Pauling et al. in rev, 10.5194/egusphere-2026-658). In a gradually warming climate, the overall result might be a reduced/delayed sea ice retreat in comparison to deep ocean warming and ice sheet retreat?

Thank you for these suggestions. We have added a sentence to the end of the intro to section 3; "Finally, basal melting of ice shelves, driven by warming deep ocean temperatures, can lead sea ice expansion, as the freshwater input and associated stratification cools the ocean surface (e.g. Purich et al., 2018)."

We have also added a sentence to the discussion of the late Holocene records, noting the link to modern ice shelf melt processes: "Using $\delta^{18}\text{O}$ of diatoms as a proxy for ice shelf meltwater in sediment cores from the Antarctic Peninsula (Pike et al., 2013), Adélie Land (Crespin et al., 2014), and Prydz Bay, Crosta et al. (2018) inferred an increase in glacial ice sheet melt and discharge around the Antarctic continental margin from ~ 4 ka onward with a coeval increase in spring sea ice in coastal regions (Crosta et al., 2018). In a similar manner to the dominance of ocean-driven basal melting of ice shelves today (Pritchard et al., 2012), the ice shelf melt inferred from ~ 4 ka was not driven by air temperatures; ice cores show a cooling at this time, so the melt must have been driven by ocean warming."

Finally, we added the following to the first paragraph of section 3.4: "Temporally resolved deglacial records from the shelf and slope could be used to assess the coupling between glacial meltwater input and sea ice growth (e.g. Purich et al. 2018). Under a scenario in which ocean warming initiates ice shelf retreat and enhanced freshwater discharge, which in turn promotes sea ice expansion, such records may indicate that sea ice retreat lags both deep-ocean warming and ice-sheet retreat during deglaciation."

L620 Replace "dynamic" with "dynamics" edited to "the dynamics of the Southern Annular Mode"

L649 Replace "This impact" with "These impacts" changed

L658 Many studies simulate increasing sea-ice associated with Southern Ocean freshening, and should provide additional insights into atmospheric impacts of expanding sea ice independently of major climatic changes. See for example Xu et al., 2025, 10.1029/2024GL113734.

Thank you for this suggestion. We have added the following to this paragraph (line 810): More recent studies that have modelled the response to increased freshwater input from Antarctic ice melt also provide insight into the atmospheric impacts of expanding sea ice. These studies consistently find that increased freshwater input to the Southern Ocean leads to sea ice expansion. The atmospheric response is likewise robust across models and attributed primarily to sea ice expansion: A cooling of the troposphere south of 35S and strengthening of the SHW (Xu et al., 2024).

L683 remove comma in "... colder, LGM..." we removed 'colder'

L836 Indirect of sea ice on productivity. What about increasing sea ice formation leading to stronger AABW formation... in turn that would presumably strengthen the lower overturning cell in the Southern Ocean, leading to more upwelling CDW, would that impact nutrient availability north of the sea-ice limit and/or northwards nutrient export in the Atlantic MOC?

Good point, we have added this sentence: “Sea-ice induced changes in the overturning circulation could also affect nutrient availability north of the sea-ice limit, by modulating the rate of upwelling of CDW.”

L862 “siliceous” is an adjective missing a noun. The sentence has been fixed

L933 add comma before “... mean that ...”. done

L966 Replace “value” with “extent”. changed

L1055 and probably elsewhere “Antarctic temperature”, would be more precisely written as “Antarctic surface air temperature”? changed

L1060 Delete “particular”. done

L1092 Replace “climate” with “climates”. done

L1093 Replace “suggest” with “suggests”. done

L1094 Replace “influence” with “influences”. done

L1106 Replace “supports for understanding” with “supports understanding of” done