nature portfolio

Peer Review File

Extremely Poleward Shift of Antarctic Circumpolar Current by Eccentricity during the Last Interglacial

Corresponding Author: Professor Xufeng Zheng

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Review Lu et al. 2024
Extremely poleward shift of Antarctic Circumpolar Current by Eccentricity during the Last Interglacial

The authors present two sortable silt record that they interpret as bottom flow speed records that are sensitive to the position and strength of the ACC. By comparing these records from the LIG to the present with time-series of eccentricity and precession, and time-series of other climate reconstructions, they try to deduce the drivers of LIG ACC changes.
What I feel is lacking in the manuscript, is a complete description of the record (LIG, glacial and Holocene) and how the records fit with other records for that whole time period and what that means in terms of possible interpretations of drivers and mechanisms. The SS records show, for instance, large differences between the LIG and the Holocene which remain unexplained. My other main concern is about the discussion of drivers, mechanisms and feedbacks. I find this discussion unclear, and more importantly, it doesn't become sufficiently clear which new information the current study brings to the table, and which are already existing ideas. Or, to put it differently, it doesn't become sufficiently clear which explaining mechanisms are out there in the literature, and to which of those the new data lends support and which ones not. Which new conclusions can be drawn from the new SS data that could not be drawn already from existing data (for instance SST data)? Please find more detailed comments below.

Major comments:

What about the Holocene?
What I miss is a discussion on the differences between the LIG and the Holocene. In many climate records, both interglacials are generally very similar. Certainly they are somewhat different, but these differences are small compared to the differences between glacials and interglacials. However, for the presented SS records this is not necessarily true. The Holocene looks more like the glacial than like the LIG. How do we interpret this? What does that mean in terms of the climate change mechanisms that are discussed in the manuscript? The manuscript now focuses very much on the LIG, but robust statements about any drivers of ACC changes should explain most of the presented time-series, not just the LIG part.

Mechanistic understanding, drivers and feedbacks
Reconstructing shifts of the ACC based on only two current velocity records located on the southward side of the Drake Passage is difficult and it is not easy to make the case that the observed changes are indeed coupled to the ACC at large. To make a stronger case, the authors rely also on previously published SST records from the broader region (Line 169). Extended Data figure 14 shows these SST records, or in fact the inferred frontal shifts, but why not show the SST records themselves? If the two indicators of ACC migration (SS and SST) are pointing in the same direction, one would like to see this.
If one looks at figure 3, the evolution of MD00-2375G in panel b seems very different from the other records, how does that fit into the overall picture? Moreover, reconstructions in panels c-g of figure 3 (perhaps also partly in h) all suggest that the situation of the LIG continued all the way up to ~80ka (not only the LIG, see line 130). By then global temperatures are certainly not above pre-industrial anymore, so the linkage with global warming, as suggested in the introduction, seems very

weak.
Lines 178-181: The temporal evolution of eccentricity is very similar to the general evolution of the glacial-interglacial cycles (perhaps not by coincidence). How do we know that the long-term behavior of the SS records is driven by eccentricity and not, for instance, driven by changes in CO2 or the size of the Antarctic Ice Sheet?
Line 181: In a coupled system like the Earth system, it is difficult to determine cause and effect. While on lines 170-174 the authors mention how a shift in the ACC can impact the Antarctic Ice Sheet, they continue on line 181 to discuss how melting of the Antarctic Ice sheet can drive changes in the ACC. While potentially both is possible in a positive feedback loop, the authors need to be much more clear about the different possible mechanisms and about what the presented records can tell us and what they can't tell us. Another example is the pathway through which eccentricity might influence the ACC. On line 178, a reference is made to Lamy et al. (2024), which describes how eccentricity influences the South Pacific jet stream and tropical Pacific temperatures, which in turn modulate the ACC. Now the authors describe a mechanism in which eccentricity influences the retreat of the Antarctic Ice Sheet, which in turn local atmospheric circulation and the ACC. The current text comes across as a mixture of all the different mechanisms and therefor seemingly contradicts itself from one paragraph to the next.
Line 211-212: I find this wording a bit too strong. You show that your records shows resemblense with eccentricity and precession, which other literature in turn has tried to connect to high and low-latitude climate change.

Minor comments:
Line 55: It seems that the time-scales of the proposed 'future' northward ACC shit, and the 'future' anthropogenic impact are very different. Please clarify and ensure that you are not comparing apples to oranges. Why speculate that the antropogenic shift is northward, while in the introduction it is mentioned that results for future shits are conflicting?

Line 70: Here there is only discussion on intensity (enhancement, no change or reduction), but in the line before 'position' is also mentioned, and it seems that position is much more relevant for the present results.

Line 140: Why is it concluded that the ACC boundary migrated poleward? Which boundary, the southern boundary? What about the northern boundary? Or, is the whole system migrating, or is it also possible that the whole system is broadening?

Figure 3:
Record PS97/093-2 very low resolution for both interglacial periods.
Why do panels i and j only show U1538 and U1537, and not for instance PS97/093-2 and PS97/085-3?

Lines 170-174: Please word this more carefully. Indeed there is research indicating that a southward shift of the ACC could ultimately increase the thermal forcing of the ice sheet. But how does one distinguish the effect on grain size of on the one hand ACC-driven bottom current changes, and on the other hand ice sheet melting-driven changes in source material? In figure 3e, we can see that SS and the percent of grain size larger than 63 µm often go hand in hand. Certainly also during the LIG and the peak in the early Holocene.

Line 206: Please specify what time-scales are involved in this natural northward shift of the ACC in the coming era. Era is rather poorly defined and it is key here for the reader to know how this natural shifts compares with a potential human-driven shift.

Line 214: "This is supported by our integrated data on precession and eccentricity". What does this mean?

Line 233-234: 'counterbalancing'. Do we know that the two effects are of similar magnitude? 'as suggested by Argo float drift observation' seems to imply that the 'counterbalancing' is already taking place. I really think the timescales should be carefully considered here. Antropogenic warming is on centennial time-scales, not 10,000 years!

Reviewer #2

(Remarks to the Author)
Review of "Extremely poleward shift of Antarctic Circumpolar Current by eccentricity during the Last Intergacial" by Lu et al.

Lu et al. aim at explain the forcing responsible for the variations in the position of the Antarctic Circumpolar Current (ACC) since the Last Interglacial (LIG) period. They do this by reconstructing its intensity with high-resolution sortable silt mean grain size analyses in two cores of the Scotia Sea, and comparing them with close-by previously published records from the area and from the Drake Passage, as well as from other location, that cover a large range of latitudes. They find maximum bottom current speeds during the LIG, that are corroborated by other records. By comparing their reconstructions with present-day transects of current velocity and assuming that the distribution pattern of the bottom speeds across the fronts remains unchanged over time, the authors deduce that the Polar Front in the Scotia Sea likely shifted poleward by ~5° during the LIG.

The datasets presented in this paper are very interesting, and the comparison with quite a few other sites is not without merit, but the results and discussion section need to be thoroughly rearranged before publication in order to present the maximum amount of information and to support the main conclusions. The discrepancies/anomalies in the records need to be explained and the conclusions better supported by the figures and the text. Below I try to give some more precise suggestions on how to achieve this.

The results presented on the “ACC velocity accelerates poleward during the LIG compared to that in the Holocene” are slightly disorganized and difficult to follow. Too much mention to the “Material and Methods” section is made, to the detriment of the readability and clarity of the paper. In order to improve this, I’d suggest to the authors to start the section with their comments on the location of the cores, and the validity of the sites for reconstructing the ACC, with a brief description of the basis of the chronology. No mention at all of the chronology is made in the main manuscript; a brief description here and a more extended explanation in the SOM is necessary. This could maybe introduce a quick discussion on sedimentation rates, the resolution of their SS analysis and why millennial-scale variability is not visible in these two cores (contrarily to the Drake Passage cores of Wu et al., (2021) that the authors cite extensively).

Then the text could move on to the chosen proxies and how they are pertinent in these locations and cores. For example, a quick discussion on the pertinence of SS vs SSFS at sites of high bottom current velocities would be appreciated. Could potential IRD values affect these records? The authors also mention that the southern and deeper core (at 59°S and 3713 m) is not significantly influenced by AABW (line 111), but this discussion is not developed or sufficiently argued. The reader is expected to know the paper of (Wu et al., 2021), where a discussion on the depth and speed of modern ACC is developed in order to assess the validity of their core locations on the Drake Passage. A similar discussion for the cores of the Scotia Sea (whose differences with the Drake Passage are quickly highlighted in lines 83-84) would be welcomed.

This section goes on describing the records and comparing them with nearby ones. The comparison with other locations is complicated for the reader, since there’s no table or figure that presents all the cores and includes their depth. Just adding the names and depth of all the cores to the caption of Figure 1 will facilitate greatly the task. Although the authors go to lengths to compare their results to distal cores, one site highly-resolved, high-impact study seems to be missing from the discussion: the Pacific sector records of (Lamy et al., 2024). How do these results compare?
Two questions come to mind when comparing these very interesting records among themselves and with others: (1) Why are Holocene SS values in IODP Site U1537 so low? They are slightly higher than LGM values, but on the same level as MIS2 or MIS3, and half the values for the same period in IODP Site U1538, while LIG values are comparable. The three-fold increase in velocity during the LIG with respect to the Holocene at IODP Site U1537 is a direct result of this. (2) Why are the increases in current velocities at the LIG much higher in the Scotia Sea than in the Drake Passage? (alternatively, is this difference between the two regions statistically significant?). A discussion on these two points would be welcomed in this section, before the discussion of supporting evidence of lines 142-158.

The discussion in the section “Potential impact of ACC frontal changes on polar upper nutrient supply” needs rearranging and some additional explanations. The premise of the discussion seems to be already that eccentricity and precession are responsible for the changes seen in both records (lines 211-214), instead of being the conclusion based on a reasoned discussion. The records the authors compare their SS to in Fig. 4e do seem to be globally in agreement, but no explanation is offered about the offset that seems to occur around 70-80 ky, that is also evident with respect to precession. This whole section needs to be made clear, specially since it presents the main conclusion highlighted in the title and the abstract of the manuscript.

Minor comments:

Fig. 1: it is difficult to see the difference between colors indicating depth and speed of surface currents. A list in the caption of names and depths of cores attached to the 1 to 12 numbers in the right figure would be useful. Please add latitudes to the blown-up location map.
Fig. 4: Please explain your choice of eccentricity+0.2precession. Power in the precession band is very low for 1387
Extended data Fig. 4e: units missing
Extended data Fig. 15: the region of high power shows mainly btw 100-120 ky, and not during 60-100 ky, which supports my previous comment that precession does not affect the whole record equally.

References:
Lamy, F., Winckler, G., Arz, H.W., Farmer, J.R., Gottschalk, J., Lembke-Jene, L., Middleton, J.L., van der Does, M., Tiedemann, R., Alvarez Zarikian, C., Basak, C., Brombacher, A., Dumm, L., Esper, O.M., Herbert, L.C., Iwasaki, S., Kreps, G., Lawson, V.J., Lo, L., Malinverno, E., Martinez-Garcia, A., Michel, E., Moretti, S., Moy, C.M., Ravelo, A.C., Riesselman, C.R., Saavedra-Pellitero, M., Sadatzki, H., Seo, I., Singh, R.K., Smith, R.A., Souza, A.L., Stoner, J.S., Toyos, M., de Oliveira, I.M.V.P., Wan, S., Wu, S. and Zhao, X., 2024. Five million years of Antarctic Circumpolar Current strength variability. Nature, 627(8005): 789-796.
Wu, S., Lembke-Jene, L., Lamy, F., Arz, H.W., Nowaczyk, N., Xiao, W., Zhang, X., Hass, H.C., Titschack, J., Zheng, X., Liu, J., Dumm, L., Diekmann, B., Nürnberg, D., Tiedemann, R. and Kuhn, G., 2021. Orbital- and millennial-scale Antarctic Circumpolar Current variability in Drake Passage over the past 140,000 years. Nature Communications, 12(1): 3948.

Reviewer #3

(Remarks to the Author)
The authors reconstruct the Antarctic Circumpolar Current (ACC) in both speed and location back to 160 ka. This dataset is novel and important for understanding past climates and is a valuable contribution to the literature. The observed connection between these currents and orbital parameters is fascinating and worthy of further study. I especially value the distincton and

discussion regarding both the ACC and the Southern Hemisphere Westerlies (SHW). I have some comments that will both help to clarify these results and give them more context within existing literature. Strengthening the argument through more explicit numbers and references in the text will be beneficial.

I would explicitly say which direction the isopycnals are tilted in the sentece on lines 59-62.

The discussion of precession's influence on the SHW could use more explanation and clarity. For example, the lines 183-185 "Due to the perihelion occurring in the southern hemisphere, the Antarctic region receives elevated solar insolation during summer." need to be clarified. Do you mean that the perihelion occurs during the southern hemisphere summer? It is also important to make a distinction between boreal (NH) and austral (SH) summer. A similar clarification needs to be made for lines 180-181.

Line 192 - Define what a precession maxima is since it is not consistent between papers. This could be done in correction made to my previous suggestion.

Line 197 change "As the precession could alter" to "As orbital precession alters" since that is objectively what precession does.

There are some modelling studies that you can reference to support your finding that orbital precession alters the strength and position of the SHW. Adding these citations will strengthen your results.
- Rutgers 2019 "Response of the High-Latitude Southern Hemisphere to Precessional Forcing: Implications for Pleistocene Ocean Circulation" finds that a high precession index causes the SHW shift poleward and intensify using GFDL.
- Persch 2023 "The Impact of Orbital Precession on Air-Sea CO2 Exchange in the Southern Ocean" also finds that a high precession index causes the SHW shift poleward and intensify using CESM.

The discussion in the lines 228-233 could use some numbers. My instinct is that the rate of change expected due to changing orbital parameters is significantly lower than the one being observed due to anthropogenic forcing, but that may not be the case. I think providing these rates would help clarify how much counterbalancing is to be expected.

Some numbers pulled from Figure 4 would help back up the claim you make in lines 202-203 that eccentricity is primary and precession is secondary.

The sentence in lines 205-206 is not a complete sentence. Adding "it is" at the beginning would fix this.

I think the discussion would benefit from drawing a connection between the observed changes in SHW and atmospheric CO2. This could be brought up as a secondary feature relative to the ACC changes, but there are many modelling studies that have sought to address this (d'Orgeville et al., 2010; Menviel et al., 2008; Tschumi et al., 2008)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I would like to thank the authors for going through all the reviewer comments and substantially revising the manuscript. As I will detail below, I still have a major concern that I would like to see addressed before publication.

Main concern:

I still find the analysis and/or presentation of the LIG to Holocene ACC changes and associated frontal positions difficult to follow and not always convincing. Perhaps I should have articulated that point more clearly in the previous round of review, although both reviewers 1 and 2 commented on it and it hasn't substantially improved.
To me, the main figures of the manuscript are 3i and 3j, they attempt to directly provide insigh into the differences between LIG and Holocene flow speeds across the ACC and possible latitudinal shifts.
Figure 3i shows the 'modern' relationship between flow speeds and Holocene reconstructed flow speeds. On lines 199-201 the authors say that they show a similar pattern. But do they really? Can one see the maxima and minima of observed flow speeds reflected in the reconstructions? Could one deduce the positions of the different fronts based on the Holocene reconstructions of flow speeds? If one plots the two measures of flow speed against each other, does one get a significant relationship?
Figure 3j is the figure that should show the reader the latitudinal migration of the ACC and assosiated fronts. The authors explain in their respons that they only show data for two cores for the LIG in figures 3i and 3j to 'provide a clearer and more region-specific understanding of front migration'. I would argue that reconstructing changes in a complex system of several fronts and several related flow speed maxima and minima, cannot be done on information from two cores alone (two cores that are also very close together so they do not add much information apart from showing that the signal is robust for that small region). Clearly the authors provide all kinds of other pieces of evidence, like sortable silt changes in other regions of

the ACC, temperature changes and d13C changes. This is also shown in figure 3a, with various sorts of red arrows. But still, like the data is currently presented, the reader mostly just has to believe that taking all this data together one finds support for a southward migration of the ACC during the LIG. I think that the authors should find a way to combine all the data into a more convincing figure.
Perhaps a way to combine all cores into a figure like 3j would be to make the x-axis into an axis that lumps together all sediment core information anywhere along the ACC between front a and b; between front b and c etc?
Another thing that could help is if the arrows in figure 3a are already 'translated' by the authors from temperature, sortable silt, d13C etc, into latitudinal shifts of the ACC. Clearly that comes with some assumptions as non of those records are proxies for 'latitudinal shifts of the ACC', but that would allow the reader to visually follow the line of reasoning of the authors as described at length in the main text.

Minor comments:

Lines 79-80: "which has profound implications for projecting their future interactions within the dynamic ice-ocean-climate system". Given that the authors show that the ACC seems mostly driven by long-term changes in eccentricity and precession, not global temperatures, I find the statement that the results of this study have profound implications for projecting future ACC changes, too strong a statement. Perhaps the authors mean with 'future' the future on orbital time-scales, but this is not sufficiently clear given that the paragraph starts with a discussion on present-day and future (IPCC-timescale). Please adjust.

Line 167: "highly likely" seems really too stronge a statement here.

Line 192: the specific mention of 'Antarctic air temperature' seems a bit odd here. I understand that the ice core data is providing this information, but to the reader it would seem strange that ACC dynamics are only compared to Antarctic air temperatures and not, for instance, Southern Ocean sea-surface temperatures. Please clarify in the text.

Technical comments:

Line 171: words missing at the end of this line.

Reviewer #2

(Remarks to the Author)
I have appreciated the effort that Lu and coauthors have done in responding to the comments, the rebuttal letter is very complete. In particular, the effort in rearranging the results and the discussion sections has made them much more complete, and they now present a clear logical development directed at supporting their conclusions. The manuscript is now easier to read and more coherent.
However, I do still feel that an explanation for the very low values of SS during the Holocene in site U1537 is still not offered, other than a (insufficient) mention to a "decoupling of Antarctic air temperature and ACC" (line 192), presumably during the Holocene. There's a more extended paragraph in the rebuttal letter, but I am afraid I do not quite grasp the explanation.
In lines 245-246 it is stated that their Holocene SS-derived current velocity is "consistent with contemporary current distribution". However, if I understand correctly their figure 3i, the Holocene values in U1538 should be lower than those in U1537 in order to be consistent with the geostrophic velocities along Jason Track 104 (green line). (Could the different patterns between Holocene-LGM and LIG-PGM between U1538 and U1537 be also the result to the differences in eccentricity?)

Abstract: in view of the anomalous very low values of the Holocene in one of the cores, the statement about the three-fold increase during LIG with respect to it seems rather not the main point. The conclusion of a southward shift of the ACC of around 5 degrees is important enough!
Lines 143-168: The low influence of AABW on the study sites is not quite well proved (although in all fairness, maybe it cannot be proved). Comparison with MD07-3076Q is used to prove that AABW is not influencing U1538 or U1537; however, this eastern South Atlantic record shows very detailed millennial-scale variability that, as the authors acknowledge, cannot be well recorded in their sites due to the sampling resolution. Also, the comparison between U1537 and PS1768-8 is used as proof of a different Holocene-LIG behaviour (thus not showing AABW); if we were to compare PS1768-8 with U1538, would the conclusions be different, seeing the higher SS Holocene values in this core? Could this be related to the different Holocene behaviour between U1537 and U1538? (i.e., an AABW influence during the Holocene in U1537, that it doesn't happen during the LIG?)
Line 171-192 and elsewhere: the uncertainties of the calculations are not shown. Even a simple standard deviation for the average values would be useful, to be able to compare different cores/periods and see if they are statistically significant or not.
Line 192: suggest the decoupling of Antarctic air temperature and ACC when? During the Holocene or during the LIG?
Line 211-213: The cited reference includes a compilation of cores at different latitudes, that are not necessarily applicable here. As their own data show, there's a Holocene-LGM difference in U1538, as in many other cores around the Southern Ocean, so I'm not sure it is the right study to cite.
Lines 225-226: the increase in ACC velocity during the LGM is interpreted as ACC acceleration and poleward shift. However, from here on, only the poleward shift is addressed. Could you explain why do you dismiss ACC acceleration? Can

you estimate how much of the SS signal could be due to it? If there's enough ACC acceleration, you may not need to invoke a poleward shift to explain the data…
Lines 260-273: Is this precessional variability also evident in U1538?
Line 312-315 and Figure 4b: Actually, the alignment between U1537 and U1361 seems to break during the Holocene: is this the "decoupling" mentioned before?
Other minor details:
Figure 1: Please add the numbers of the cores together with the names, i.e. (1) TPC063, 3956 m, (2) TPC077, 3774 m, and so on. As there's 13 of them, this will greatly facilitate their identification.
Line 42: Please add "a" in "playing a key role"
Line 98: Please change "Dronning" to "Dome" (EDC stands for EPICA Dome C)
Line 103: Instead of 'sampling increments' in m (and sedimentation rates in cm/ka), it would be more straightforward to talk about sampling resolution in age.
Is Supplementary Figure 4 cited before Supplementary Figure 5?
Line 118: Please change 'has' for 'have'
Line 121: "ACC flow speeds can achieve flow speeds" – please remove one of the flow speeds.
Line 128: Please change 'observation' to 'observations'
Line 147: Please change 'Views' by 'View'
Line 165: With the 'temporal pattern', you mean the temporal changes between the two cores? With the addition of the lines before, this sentence now needs to be rephrased.
Line 171: exhibits stable what? Please rephrase.
Line 624: Please change 'tracer' to 'tracers'
Line 719: Please remove 'below'

Reviewer #3

(Remarks to the Author)
After reviewing the changes made by the authors in response to comments, I feel that my concerns have been adequately addressed. The manuscript has been significantly improved in response to my and the other reviewer's comments. I feel that it is ready for publication and will serve as an important contribution to the field.

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Review Lu et al. 2024
Extremely poleward shift of Antarctic Circumpolar Current by Eccentricity during the Last Interglacial

The manuscript has again significantly improved and I thank the authors for their efforts. I still have some minor and technical comments, but overall I think the manuscript is now sufficiently clear and nearly ready for publucation.

Minor comments:
Line 329: The period 70-80ka is mentioned as being different from the mechanism described above, but isn't the period before ~130ka also different?

Line 339: How does this study suggest a link between ACC shifts and tropical climate variability? Please clarify in the text what you are refering to.

Line 359: how consistent is the SS record at U1537 really with the d15N and CO2 offset record (figure 4e)? Can you provide some type of quantification of this consistency?

Figure 2: I think it is worthwhile to note somewhere in the manuscript that the inferred ACC shifts do not fully align in time with the LIG. As is clear from figure 2 and mentioned in the text, the high SS values are found around 120-113ka, while the peak interglacial temperatures are generally considered to have occurred before 125ka and the temperature plateau in figure 4a would be ~127-118ka. Perhaps this is consistent with a dominant orbital forcing over the imprint of the glacial-interglacial cycle?

Figure 3i: the figure would be visually even more convincing if the two 'data points' towards the northern part of this transect would not be given in terms of relative changes in their native interpretation (STF shifts in GeoB-3603-2 and temperature changes in PS75/034-2) but in terms of their implied changes in ACC position. In that way they would show negative relative changes while all data south of that would show positive relative changes (assuming that MD00-2375G would also be negative speed changes in contrast to what is shown now). Perhaps the authors regard such a figure as too much interpretation and too little raw data.

Technical comments:
Line 57: "~45°S and"

Line 62: Comma after “fronts”?
Line 66: “changes in the ACC’s position”?
Line 81: “topografic constraint”?
116: Does the reader know what SS% or SSFS% are?
Line 211: SAF is SAF-S in figure 3h?
Line 234: Don’t start the new paragraph with ‘whereas’
Line 251: Remind the reader to which core, data and/or figure you are refering to when speaking about the current speeds at Drake Passage.
Line 262: shouldn’t the value of the relative change in flow speeds of MD00-2375G be negative in figure 3i?
Line 264: clarify which core and/or data point in figure 3i you are refering to with ‘Cape Basin’.
Lines 320-323: Don’t you already discuss the detrended SS data from sites U1537 and U1538 above? So you cannot introduce it here as ‘further evidence’ for you line of reasoning?

Reviewer #2

(Remarks to the Author)
I thank the authors for the substantial effort they have done in answering my and the other reviewers’ previous comments, I feel that the manuscript has greatly evolved and shifted its focus towards a more clear message. It is now very much improved and ready for publication.

Point-by-point response to the reviewers' comments

Reviewer #1 (Comments to Author (shown to authors):

1. The authors present two sortable silt record that they interpret as bottom flow speed records that are sensitive to the position and strength of the ACC. By comparing these records from the LIG to the present with time-series of eccentricity and precession, and time-series of other climate reconstructions, they try to deduce the drivers of LIG ACC changes.

What I feel is lacking in the manuscript, is a complete description of the record (LIG, glacial and Holocene) and how the records fit with other records for that whole time period and what that means in terms of possible interpretations of drivers and mechanisms. The SS records show, for instance, large differences between the LIG and the Holocene which remain unexplained.

Response:

Thank you very much for your thoughtful and constructive feedback on the need for a more comprehensive description of the sortable silt mean grain size ($\overline{SS}$) records across the Last Interglacial (LIG, 128-113 ka), glacial, and Holocene (10-0 ka), as well as their integration with other climate records to better interpret the drivers and mechanisms of change. To fully address this, we have carefully revised the manuscript accordingly.

(1) We have extended the description of the $\overline{SS}$ records at Sites U1538 and U1537 to provide a more complete overview of changes during the LIG, glacial, and Holocene. At Site U1537 $\overline{SS}$ values are relatively low and stable during the Penultimate Glacial Maximum (PGM, 158-135 ka; average $\overline{SS}$ = 16.31 μm). In comparison, during the same period, Site U1538, located within the Southern Antarctic Circumpolar Current front (SACCF), shows slightly higher $\overline{SS}$ with an average $\overline{SS}$ of 17.77 μm. $\overline{SS}$ values converge at both sites, displaying almost identical peak values (21.44 μm and 21.48 μm) during the LIG. In contrast, the Holocene $\overline{SS}$ values at Site U1538 only show a slight increase relative to the Last Glacial Maximum (LGM, 26-19 ka) ($\overline{SS}_{U1538\text{-}Holoecne}$ =18.96 μm; $\overline{SS}_{U1538\text{-}LGM}$ =16.62 μm) and the $\overline{SS}$ at Site U1537 for the Holocene and LGM are nearly identical ($\overline{SS}_{U1537\text{-}LGM}$ = 16.20 μm, average $\overline{SS}_{U1537\text{-}Holoecne}$= 16.06 μm) regardless of the 11°C Antarctic air temperature contrast between the Holocene and the LGM[1]. This temperature difference is similar to that between the LIG and PGM (12 °C) in the Antarctic ice core record. The contrasting transition patterns in $\overline{SS}$ between the LIG and Holocene, which are considered climatically similar, suggesting the decoupling of Antarctic air temperature and ACC. Please see lines 171-192 in Main Text, Figs. 2b and 2c, and Supplementary Fig. 13.

(2) As suggested, we have incorporated additional comparisons of temporal changes in our $\overline{SS}$ records with proxy data, focusing on the Scotia Sea and Drake Passage, while incorporating data from the Pacific sector of the Southern Ocean and expanding the discussion on climatic drivers of bottom flow speed changes. These comparisons provide valuable context for understanding the broader patterns of the Antarctic Circumpolar Current (ACC) and climate change, meanwhile, revealing regional differences to help clarify the substantial discrepancies in our record between the Holocene and LIG.

- ✓ Specifically, we find that the reconstructed flow velocities from our cores and previously reported cores across the Drake Passage and Scotia Sea during the Holocene exhibited a similar pattern with these modern observations[2], showing higher velocities around the Polar Front (PF) and Subantarctic Front (SAF) and lower velocities to the south of the SACCF. ACC speeds during the LGM were lower relative to Holocene at multiple locations in the main fronts of the Drake Passage and the Scotia Sea, for example, decreased by 3.8 cm/s at Site PS97/093-2 (~40 km NW of the SAF, 3781 m)[3], 5.1 cm/s at Site PS97/085-3 (~40 km north of the PF, 3837 m)[4], and 4.4 cm/s at Site U1538 (SACCF) (Fig. r1a). This LGM decrease in ACC flow speed can be observed even in the central South Pacific[5]. However, the ACC velocities at Site U1537, located to the south of the SACCF in the Scotia Sea, were found to be low both in the LGM and the Holocene, and this relatively stable and low current velocities phenomenon had been reported previously in the Scotia Sea[6]. The above compilation suggests that the ACC intensity reduced considerably during the LGM, while the course configuration of the ACC front in the Scotia Sea and the Drake Passage remained relatively unchanged. This interpretation is supported by similar glacial and Holocene planktonic foraminiferal $\delta^{18}O$ distributions observed in both the Atlantic and Pacific sectors of the Southern Ocean[7]. Please see lines 194-213 in Main Text, Fig. 3, and Supplementary Fig. 14.

- ✓ Whereas during the stabilized interval of the LIG (123-118 ka), there was a widespread increase in current speed encompassing the fronts within the Drake Passage and Scotia Sea. For locations in the Pacific entrance to the Drake Passage ~40 km NW of the SAF (PS97/093-2, 3781 m)[3] and in the central Drake Passage ~40 km north of the PF (PS97/085-3, 3837 m)[4], the current speed increased by 1.1 cm/s and 2.9 cm/s, respectively (Fig.r1b). Interestingly, these increments are relatively small compared with the ones at Sites U1538 (increased by 6.0 cm/s) near the SACCF and U1537 (increased by 10.6 cm/s) south of the SACCF in the Scotia Sea (Fig.r1b). Notably, an increase in current speed was also recorded in the pelagic central South Pacific[5], suggesting that the basin-wide acceleration of currents during the LIG extended beyond the Drake Passage and Scotia Sea. The increasing ACC velocity with latitudes, particularly pronounced at the southernmost stations, indicates ACC acceleration and a poleward shift during the LIG. Please see lines 215-242 in Main Text, Fig. 3, and Supplementary Fig. 14.

✓ To further explore the climatic drivers, we now include a more detailed comparison of our records with Earth's orbital parameters, Southern Hemisphere westerlies, Intertropical Convergence Zone, and other proxy data, specifically looking at the influence of Earth's orbital parameters on the ACC through the South Hemisphere westerlies, and the potential impact of the ACC on ice sheet dynamics. Please see lines 260-315 in Main Text, Fig 4, and Supplementary Figs. 17 and 18.

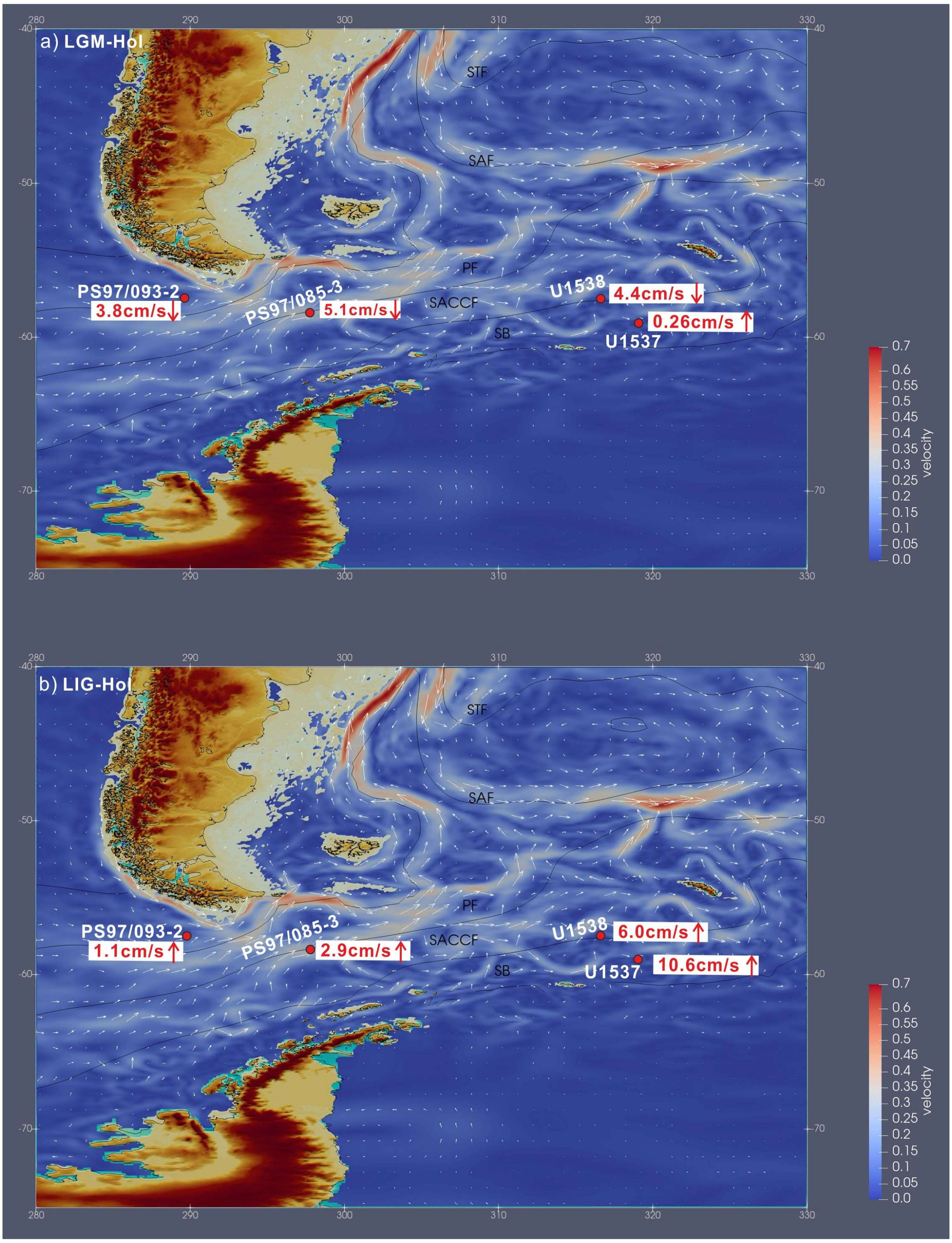

Fig.r1 | Comparisons of ACC flow speed in the Scotia Sea and Drake Passage[3,4] between the Last Glacial Maximum (LGM) and Holocene (Hol) (a), and between the Last Interglacial (LIG) and Hol (b). Base map using the MDT_CNES_CLS18_global data set[8] shows the global ocean surface current, with warmer red colors representing higher current speeds.

2. My other main concern is about the discussion of drivers, mechanisms and feedbacks. I find this discussion unclear, and more importantly, it doesn't become sufficiently clear which new information the current study brings to the table, and which are already existing ideas. Or, to put it differently, it doesn't become sufficiently clear which explaining mechanisms are out there in the literature, and to which of those the new data lends support and which ones not. Which new conclusions can be drawn from the new SS data that could not be drawn already from existing data (for instance SST data)? Please find more detailed comments below.

Response:

In this version, we have thoroughly revised the manuscript to clarify the novelty of our study, specifically regarding the drivers, mechanisms, and feedback involved:

(1) Site U1537 located south of SACCF (near the Southern Boundary of ACC), provides a crucial high-resolution, continuous record of ACC variability from the southernmost region. Meanwhile, our results show that bottom flow speeds to the south of the SACCF during the LIG were nearly three times higher than those during the Holocene, distinct from many climate record patterns, such as SST data. Please see Fig. 2, lines 185-192 in the Main Text.

(2) Moreover, our $\overline{SS}$ reveals pronounced orbital-scale modulation of ACC dynamics, demonstrating the coupled influence of eccentricity and precession on shifting of South Hemisphere westerlies in driving the ACC front migration, with a potential impact on the Antarctic ice sheet. Through several combination tests, we quantified the relative contributions of orbital parameters, showing that a combination of eccentricity and 0.2 precession jointly influences ACC front migration, with low-frequency eccentricity acting as the primary natural forcing and precession as secondary. Thus, our study advances the understanding of the complex and dynamic interplay between natural factors, such as orbital forcing, South Hemisphere westerlies, the ACC front migration, and Antarctic ice sheet dynamics. Our study also emphasizes that the tropical region is a crucial area for transferring long-term climate signals from low and mid-to-high latitudes in the Southern Hemisphere. Moreover, we highlight the impacts of ACC fronts change, that is, moving the upwelling center southward to promote upwelling of nutrient- and CO_2-rich waters. Please see Fig. 4, lines 260-296, 306-332 in the Main Text.

(3) Based on the aforementioned findings, our work suggests that the ACC course position would gradually shift northward under natural conditions in the future in response to a decrease in eccentricity and precession. Overall, our findings might

help to elucidate how the contemporary ocean pattern might be influenced by the climate system and contribute to an enhanced understanding of the behavior of the ACC and its intricate interactions within the dynamic ice-ocean-climate system. Please see lines 336-339 in the Main Text.

3. What about the Holocene?

What I miss is a discussion on the differences between the LIG and the Holocene. In many climate records, both interglacials are generally very similar. Certainly they are somewhat different, but these differences are small compared to the differences between glacials and interglacials. However, for the presented SS records this is not necessarily true. The Holocene looks more like the glacial than like the LIG. How do we interpret this? What does that mean in terms of the climate change mechanisms that are discussed in the manuscript? The manuscript now focuses very much on the LIG, but robust statements about any drivers of ACC changes should explain most of the presented time-series, not just the LIG part.

Response:

We sincerely thank the reviewer for the insightful comments and constructive suggestions, which have greatly helped us improve the manuscript. We have extended the manuscript to explore the discrepancies and drivers for the LIG and the Holocene in greater detail.

(1) To assess the differences between the LIG and Holocene, we have compiled additional proxy data from beyond the Scotia Sea. This broader perspective highlights regional variations in ACC dynamics to help clarify the substantial discrepancies in our record between the Holocene and LIG. Notably, our findings reveal that compared with the Holocene, the ACC intensity reduced considerably during the LGM, while the course configuration of the ACC front in the Scotia Sea and Drake Passage remained largely unchanged. In contrast, the ACC acceleration and poleward shift during the LIG. Please see our detailed first reply to reviewer #1.

(2) To gain deeper insights into the climatic drivers during the LIG and Holocene, we conducted an extensive comparison of our records with Earth's orbital parameters, Southern Hemisphere westerlies, the Intertropical Convergence Zone, and various proxy data spanning the entire time series, encompassing both the LIG and Holocene. This analysis offers a more robust interpretation of the mechanisms driving ACC variability across different climatic states. Our findings indicate that a combination of eccentricity and the 0.2 precession jointly influence the migration

of the ACC front through the Southern Hemisphere westerlies. Specifically, low-frequency eccentricity emerges as the primary natural forcing, while precession plays a secondary role. The highest $\overline{SS}$ observed during periods of maximum eccentricity in the Interglacial, correspond to the southernmost position of the ACC. Conversely, the lowest stable $\overline{SS}$ recorded during periods of minimum eccentricity during the Holocene and LGM, further support a primary role of eccentricity in the ACC dynamics. Please see lines 260-296 in Main Text and Fig.4.

> 4. Mechanistic understanding, drivers and feedbacks
>
> Reconstructing shifts of the ACC based on only two current velocity records located on the southward side of the Drake Passage is difficult and it is not easy to make the case that the observed changes are indeed coupled to the ACC at large. To make a stronger case, the authors rely also on previously published SST records from the broader region (Line 169). Extended Data figure 14 shows these SST records, or in fact the inferred frontal shifts, but why not show the SST records themselves? If the two indicators of ACC migration (SS and SST) are pointing in the same direction, one would like to see this.

Response:

We greatly appreciate your suggestion to directly compare Sea Surface Temperature (SST) records with our current velocity data to enhance the robustness of our reconstruction of ACC shifts. We agree that relying solely on two current velocity records from the southward side of the Drake Passage presents limitations in representing ACC dynamics at large. To address this, we have expanded our analysis by integrating previously published SST records across a broader region, which are now systematically compiled in Supplementary Fig. 16. This broader dataset provides a more comprehensive view of regional temperature patterns and helps mitigate the spatial limitations of the current velocity records.

Regarding your question about Extended Data Fig. 14 (Supplementary Fig. 16 in this revised manuscript), we chose to show the inferred frontal shifts rather than the raw SST records to focus on the interpreted patterns relevant to ACC migration. However, we recognize the value of presenting the raw SST data to demonstrate consistency between the SST and current velocity indicators. In response to your comment, we have included the raw SST records (PS75/034-2[9]) in Fig. r2a (Supplementary Fig. 15 in this revised manuscript), to clearly show the alignment between the two datasets. This will allow readers to directly assess the correlation between SST and current velocity changes, further strengthening the case for coupled ACC dynamics. Please see lines

230-236 and 248-254 in Main Text, Fig. 3 and Supplementary Fig. 15 and Fig. r2a.

Finally, we have also compiled ACC flow speed records from multiple oceanic regions (PS97/093-2[3], PS97/085-3[4], U1541[5], U1538, and U1537) and incorporated a published proxy for the relative position of the Subtropical Convergence (STC)[10]. The STC index, calculated as the ratio of G. truncatulinoides to (N. pachyderma (dex.) + G. inflata + G. truncatulinoides), was derived from sediment cores in the southern Cape Basin, located between the Indian and Atlantic Oceans[10] (Fig. r2b). By combining the multi-proxy SST dataset, ACC flow speed records, and the STC proxy, we have created a cohesive framework that aligns with and robustly supports our interpretations of frontal dynamics. This integrated approach strengthens the validity of our findings and provides a more nuanced understanding of ACC shifts Please see lines 215-242 in Main Text, Fig. 3 and Supplementary Fig. 15 and Fig. r2b.

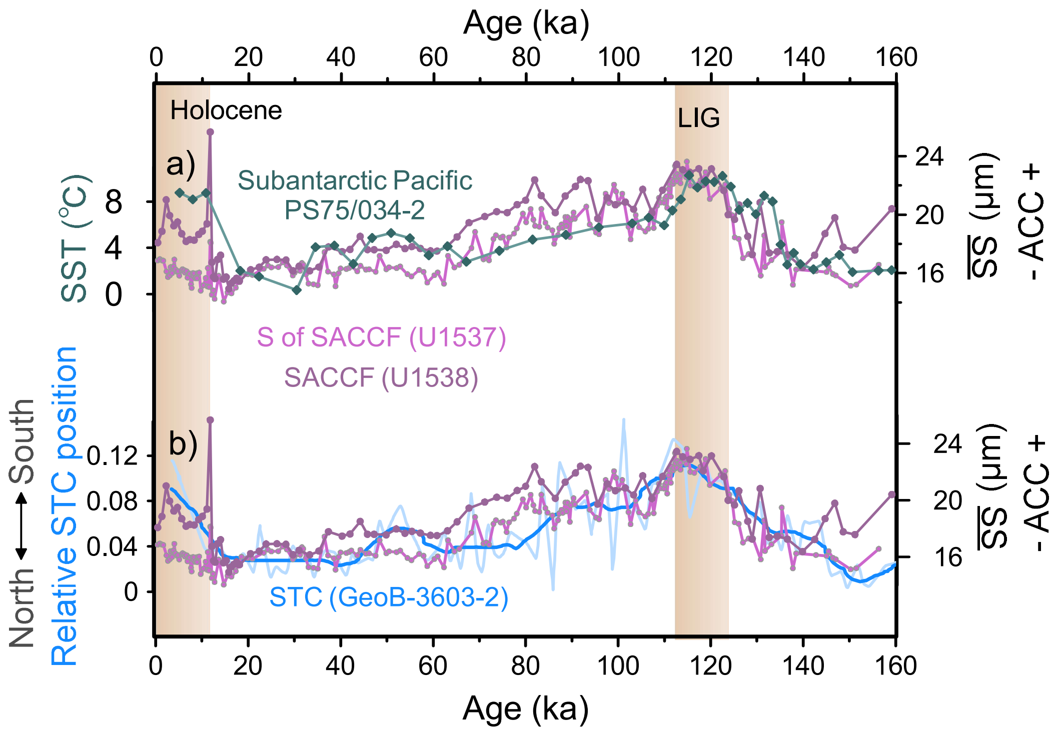

Fig.r2 | The comparisons of $\overline{SS}$ at Sites U1537 and U1538 with Sea Surface Temperature (SST) record at subantarctic Pacific (PS75/034-2)[9] and relative STC position, derived from the ratio of G. truncatulinoides / (N. pachyderma (dex.) + G. inflata + G. truncatulinoides) in the southern Cape Basin (GeoB-3603-2)[10].

5. If one looks at figure 3, the evolution of MD00-2375G[11] in panel b seems very different from the other records, how does that fit into the overall picture? Moreover, reconstructions in panels c-g of figure 3 (perhaps also partly in h) all suggest that the situation of the LIG continued all the way up to ~80ka (not only the LIG, see line 130). By then global temperatures are certainly not above pre-industrial anymore, so the linkage with global warming, as suggested in the introduction, seems very weak.

Response:

Thank you for your insightful comments regarding the evolution of the MD00-2375G record in Fig. 3b and the implications for the linkage to global warming.

Regarding the apparent difference in the MD00-2375G record, we have compared it with our U1537 and U1538 records. As shown in Fig. r3, MD00-2375G exhibits an inverse pattern of ACC strength compared to U1537 and U1538. Given that MD00-2375G is located near the northern boundary of the ACC, we interpret these opposing trends as a direct response to frontal migration. A pronounced southward shift of the ACC fronts would reduce northern transport while enhancing southern flow, consistent with the observed patterns. This interpretation is further supported by reconstructions from additional sites (PS97/093-23, PS97/085-34, and U1541 in Fig. 3c-g), which collectively show sustained high values from the LIG to ~80 ka, robustly supporting a southward ACC displacement during this interval. Please see lines 236-239 in Main Text and Fig. 3 for further details.

Regarding the persistence of high ACC speeds from the LIG to ~80 ka, we agree with the reviewer that the connection to global warming is weak. We have therefore removed the related content in the introduction (see lines 68-78 in the Main Text). However, the persistence of these conditions highlights the long-term response of the ACC to orbital forcing and other regional drivers, which remains an important aspect of our study. We appreciate your comment and have adjusted the manuscript accordingly.

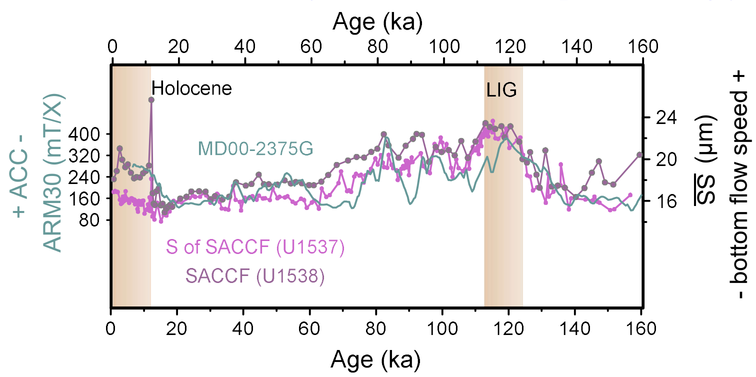

Fig.r3 | The comparisons of $\overline{SS}$ data at Sites U1537 and U1538 and ARM 30 at Site MD00-2375G[11].

6. Lines 178-181: The temporal evolution of eccentricity is very similar to the general evolution of the glacial-interglacial cycles (perhaps not by coincidence). How do we know that the long-term behavior of the SS records is driven by eccentricity and not, for instance, driven by changes in CO_2 or the size of the Antarctic Ice Sheet?

Response:

We sincerely thank the reviewer for these valuable comments. We fully agree that the temporal evolution of eccentricity closely aligns with the general pattern of glacial-interglacial cycles, and we acknowledge the challenge of disentangling the influences of eccentricity, CO_2, and the Antarctic Ice Sheet on the long-term behavior of the $\overline{SS}$ records. To address this, we have now included these factors together in Fig. r4 to facilitate comparison.

In our analysis, we observe that the $\overline{SS}$ records exhibit a strong correlation with eccentricity, which we interpret as evidence that orbital-scale forcing plays a significant role in modulating ACC dynamics. Eccentricity is an external forcing factor that alters Earth's distance from the Sun, modulating total solar insolation and seasonal radiation patterns. This, in turn, can amplify interhemispheric energy gradients and drive changes in the Earth system, including the ACC. However, we recognize that internal feedback mechanisms, such as CO_2 levels and Antarctic Ice Sheet size, may also influence the $\overline{SS}$ records. Fig. r4 shows that while eccentricity aligns well with the $\overline{SS}$ records, CO_2, and ice sheet variations also exhibit some correspondence, suggesting that these factors may contribute to the observed patterns.

At this stage, our study cannot definitively isolate the relative contributions of eccentricity, CO_2, and the Antarctic Ice Sheet to the long-term behavior of the ACC. Resolving these interactions will require long-term, high-resolution records extending beyond the 160-ka timeframe of our current study, as well as refined chronological frameworks. We hope that future work, including modeling studies and additional paleoceanographic records, will help clarify these relationships. Please see Fig. r4 for a visual comparison of these factors.

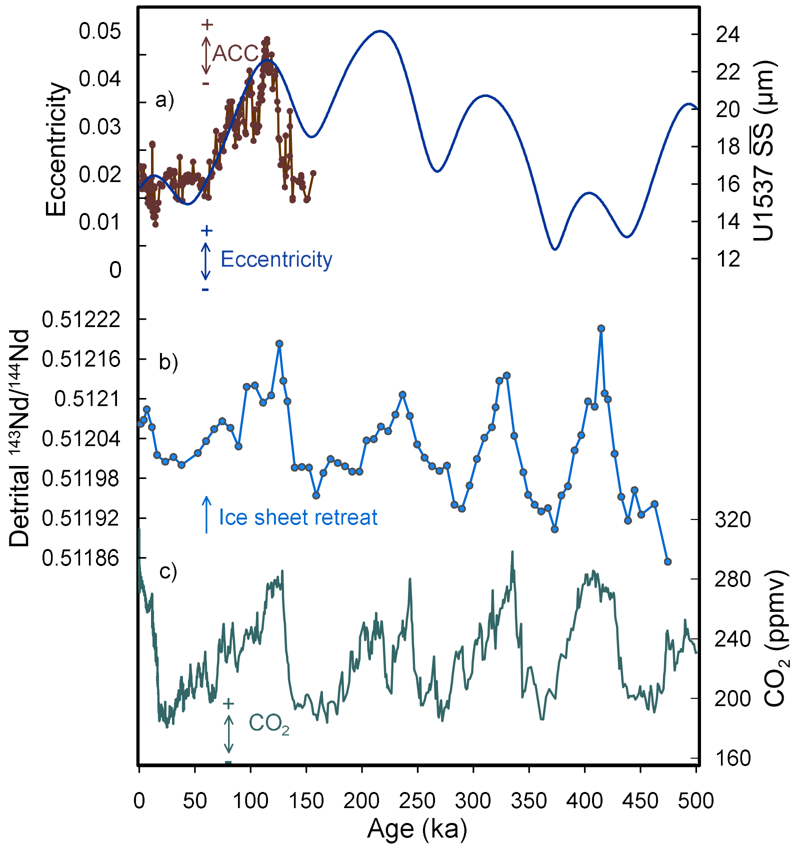

Fig.r4 | The comparisons of $\overline{SS}$ data at Site U1537 (ACC) with eccentricity (a)[12], Antarctic Ice Sheet change inferred by detrital sediment Nd isotopes records at Site U1361A (b)[13], and CO_2 records (c)[14].

7. Line 181: In a coupled system like the Earth system, it is difficult to determine cause and effect. While on lines 170-174 the authors mention how a shift in the ACC can impact the Antarctic Ice Sheet, they continue on line 181 to discuss how melting of the Antarctic Ice sheet can drive changes in the ACC. While potentially both is possible in a positive feedback loop, the authors need to be much more clear about the different possible mechanisms and about what the presented records can tell us and what they can't tell us. Another example is the pathway through which eccentricity might influence the ACC. On line 178, a reference is made to Lamy et al. (2024)[5], which describes how eccentricity influences the South Pacific jet stream and tropical Pacific temperatures, which in turn modulate the ACC. Now the authors describe a mechanism in which eccentricity influences the retreat of the Antarctic Ice Sheet, which in turn local atmospheric circulation and the ACC. The current text comes across as a mixture of all the different mechanisms and therefor seemingly contradicts itself from one paragraph to the next.

Response:

Thank you very much for your constructive feedback. We greatly appreciate your insights and have revised the manuscript to address your concerns about clarity and consistency in the description of the mechanisms.

(1) Regarding the interaction between the ACC and the Antarctic Ice Sheet, we agree that the cause-and-effect relationships in a coupled system like the Earth system can be complex and that our original text may have appeared contradictory. To address this, we have revised the discussion to clearly state that our records suggest a correlation between ACC shifts and changes in the Antarctic Ice Sheet, with orbital-scale shifts in the ACC front possibly playing a crucial role in driving these interactions. We have removed any contradictory statements regarding Antarctic Ice Sheet-driven changes in the ACC. Please see lines 254-257 and 309-315 in the Main Text and Fig. 4.

(2) For the role of eccentricity in modulating the ACC, we have revised the discussion to clarify the pathways through which it might influence the ACC. Specifically, we now propose that orbital eccentricity's modulation of precession and tropical climate affects the strength and position of the Southern Hemisphere Westerlies and the movement of ACC fronts. We have removed any overlapping or contradictory statements. Please see lines 260-296 in the Main Text and Fig. 4.

> 8. Line 211-212: I find this wording a bit too strong. You show that your records shows resemblense with eccentricity and precession, which other literature in turn has tried to connect to high and low-latitude climate change.

Response:

Thank you for pointing out the wording in Lines 211-212. To improve clarity, we have revised the sentence as follows: "Our study suggests the orbital-scale shifts in the ACC front are linked to tropical climate variability." Please see lines 308-309 in the Main Text.

Minor comments:

> 9. Line 55: It seems that the time-scales of the proposed 'future' northward ACC shit, and the 'future' anthropogenic impact are very different. Please clarify and ensure that you are not comparing apples to oranges. Why speculate that the natural shift is northward, while in the introduction it is mentioned that results for future shits are conflicting?

Response:

Thank you very much for your insightful comments. We fully agree with the reviewer that the timescales of the natural proposed ‘future’ northward ACC shift and the anthropogenic impact differ significantly. To clarify, the northward shift of the ACC that we suggest is based on the long-term trends in orbital parameters (decreasing trend in eccentricity and precession). Thus the timescale of this proposed ‘future’ northward ACC is on orbital changes and is expected to occur over thousands of years. On the other hand, anthropogenic warming, which operates on centennial timescales, may influence or interfere with this shift. We have revised the manuscript as follows: “ We propose that the low-frequency ACC frontal migration is primarily controlled by eccentricity-driven shifts in the Southern Hemisphere Westerlies, while precession-driven shifts contribute to high-frequency migration. Our findings imply under future orbital-scale scenarios, the ACC position is likely to shift north.” These revisions clearly reflect the difference between natural and anthropogenic timescales. Please see lines 50-54 and 68-78 in Main Text.

> 10. Line 70: Here there is only discussion on intensity (enhancement, no change or reduction), but in the line before ‘position’ is also mentioned, and it seems that position is much more relevant for the present results.

Response:

Thank you very much for your valuable suggestion. We greatly appreciate your insight, which has helped us improve the clarity of this section. Following your suggestion, we have revised the sentence as follows: “Significant concern has been raised for future ocean and climate regarding the possibility of ACC position. This concern remains, as models and observations present conflicting results, including a poleward shift and no change.” Please see lines 68-70 in Main Text.

> 11. Figure 3: Record PS97/093-2 very low resolution for both interglacial periods. Why do panels i and j only show U1538 and U1537, and not for instance PS97/093-2 and PS97/085-3?

Response:

Thank you very much for your thoughtful comment. While it is true that record PS97/093-2[3] has a relatively low resolution for both interglacial periods, its results are generally in good agreement with those from PS97/085-3[4], U1538, and U1537 (Fig.r5). We excluded PS97/093-2 and PS97/085-3 from panels i and j as their locations in the Drake Passage are geographically distinct from the Scotia Sea study area. In the regions of the Drake Passage, the ACC flow is relatively stronger, with flow velocities on a different order of magnitude compared to the Scotia Sea. To maintain a consistent and comparable framework for analyzing ACC dynamics and front migration, we focused on sites within the Scotia Sea. This allows us to provide a clearer and more region-specific understanding of front migration. Please see Supplementary Fig. 10.

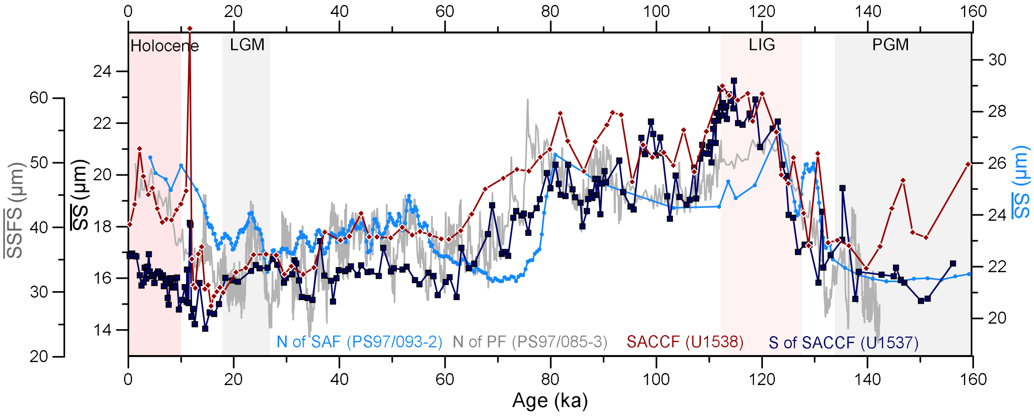

Fig.r5 | Comparisons of ACC records within the Scotia Sea and the Drake Passage, including $\overline{SS}$ at Sites PS97/093-2[4], U1538 and U1537, as well as $\overline{SSFS}$ at Site PS97/085-3[3].

12. Lines 170-174: Please word this more carefully. Indeed there is research indicating that a southward shift of the ACC could ultimately increase the thermal forcing of the ice sheet. But how does one distinguish the effect on grain size of on the one hand ACC-driven bottom current changes, and on the other hand ice sheet melting-driven changes in source material? In figure 3e, we can see that SS and the percent of grain size larger than 63 μm often go hand in hand. Certainly also during the LIG and the peak in the early Holocene.

Response:

Thank you for your thoughtful and insightful comment. We appreciate your suggestion to refine the wording in this section for clarity. We have carefully revised the word as below: "The 5° poleward movement of the PF would likely enhance the intrusion of Circumpolar Deep Water onto the Antarctic shelves, leading to de-stabilization and mass loss of the Antarctic Ice Sheets from underneath by ocean thermal forcing, influencing the global sea level, ocean circulation, and global climate". Please see lines 254-257 in Main Text.

Although we observed a correlation between $\overline{SS}$ and grain size larger than 63 μm in Fig. 3e, grains larger than 63 μm typically comprise a small fraction of the total sediment volume (less than 5%). This indicates that changes in source material due to ice sheet melting play a minor role in the observed grain size variations. Please see lines 133-139 in Main Text.

On the other hand, a much stronger correlation between $\overline{SS}$ and SS% (R^2=0.93) indicates that variations in grain size are more strongly associated with bottom current (ACC) dynamics than ice sheet melting-driven changes in the sediment source material. We have revised the manuscript to more carefully address these points and to clarify the mechanisms driving the observed patterns. Please see lines 139-141 in Main Text.

> 13. Line 206: Please specify what time-scales are involved in this natural northward shift of the ACC in the coming era. Era is rather poorly defined and it is key here for the reader to know how this natural shifts compares with a potential human-driven shift.

Response:

Thank you very much for your valuable comment. We apologize for the vague use of "era" in line 206 and appreciate your suggestion to clarify the time scales. The time scales of the ACC shifts we discuss in the manuscript are on the order of tens of thousands to hundreds of thousands of years, as the ACC shifts are driven by long-term variations in precession and eccentricity. We have revised the manuscript to more clearly define the "coming era" as follows: "It is worthwhile to note that the natural forcing would move ACC northward in the coming era (i.e., during the next 10,000 years) due to orbital change". These revisions could distinguish it from the faster, centennial-scale human-driven shifts currently observed. Please see lines 296-298 in the Main Text.

> 14. Line 214: "This is supported by our integrated data on precession and eccentricity". What does this mean?

Response:

We apologize for the unclear sentence. We have carefully revised this in the updated version of the manuscript as follows: "The overall temporal variation pattern of U1537 $\overline{SS}$, most consistent with the combination of eccentricity and a 0.2 precession, suggest that the low-frequency eccentricity potentially acts as the primary natural forcing and the precession as the secondary means". Please see lines 293-296.

15. Line 233-234: ‘counterbalancing’. Do we know that the two effects are of similar magnitude? ‘as suggested by Argo float drift observation’ seems to imply that the ‘counterbalancing’ is already taking place. I really think the timescales should be carefully considered here. Antropogenic warming is on centennial time-scales, not 10,000 years!

Response:

We fully agree that the relative magnitudes of natural and anthropogenic processes differ significantly. ACC shifts driven by long-term variations in precession and eccentricity occur over tens to hundreds of thousands of years, whereas anthropogenic warming operates on centennial timescales. To avoid any misunderstanding, we have revised the wording to clarify the different magnitude. Please see lines 336-341 in the Main Text.

Additionally, we have clarified Argo float drift observations as follows: “Current Argo float drift observations suggest that, at least in the short term, the ACC position has experienced only minor changes.” We have also carefully considered the differences in timescales. Please see lines 341-347 in the Main Text.

Reviewer #2 (Comments to Author (shown to authors):

1. Lu et al. aim at explain the forcing responsible for the variations in the position of the Antarctic Circumpolar Current (ACC) since the Last Interglacial (LIG) period. They do this by reconstructing its intensity with high-resolution sortable silt mean grain size analyses in two cores of the Scotia Sea, and comparing them with close-by previously published records from the area and from the Drake Passage, as well as from other location, that cover a large range of latitudes. They find maximum bottom current speeds during the LIG, that are corroborated by other records. By comparing their reconstructions with present-day transects of current velocity and assuming that the distribution pattern of the bottom speeds across the fronts remains unchanged over time, the authors deduce that the Polar Front in the Scotia Sea likely shifted poleward by ~5° during the LIG. The datasets presented in this paper are very interesting, and the comparison with quite a few other sites is not without merit, but the results and discussion section need to be thoroughly rearranged before publication in order to present the maximum amount of information and to support the main conclusions. The discrepancies/anomalies in the records need to be explained and the conclusions better supported by the figures and the text. Below I try to give some more precise suggestions on how to achieve this.

Response:

We greatly appreciate your valuable feedback and detailed suggestions. We have carefully revised the Results and Discussion section to address the raised issues according to the reviewer, to present the maximum amount of information and to support the main conclusions. Moreover, we have added more explanations about the anomalies in the records and redrawn some figures to better support our conclusions.

(1) To present the maximum amount of information and to support the main conclusion, in the revised manuscript, we have added a concise description of the core locations and their suitability for reconstructing ACC dynamics, as well as a brief explanation of the chronology. Additionally, we have discussed sedimentation rates, the applicability of $\overline{SS}$ versus $\overline{SS}FS$, the suitability of $\overline{SS}$ at our cores. We have also provided explanations to exclude the potential influences on our records, including the Antarctic Bottom Water (AABW) impact on Site U1537 and the potential ice-rafted debris (IRD, >150 μm) influence. We have further extended our discussion with comparisons to datasets from the Scotia Sea, Drake Passage, and the Pacific sector, offering a broader perspective to understand the ACC dynamics. Finally, we have included a detailed comparison with global paleoclimate datasets (e.g.,

Southern Hemisphere Westerlies, Intertropical Convergence Zone records) and orbital parameters to further explore the potential climatic drivers, and discussed the implications for the Antarctic Ice Sheet, polar nutrient supply, and atmospheric CO_2 concentrations. Please see lines 89-332 in the Main Text.

(2) We have extended the discussion on the anomalies in our records, for example, the significant differences in bottom current speeds between the LIG and Holocene, as well as the lower power during 70-80 ka. These anomalies are examined in detail, with potential mechanisms explored to provide a clearer understanding. Please see lines 185-228 and 298-303 in the Main Text.

(3) We have revised the figures to more robustly support our key findings. By addressing the anomalies and integrating comparative data, we believe the revised manuscript provides stronger support for the conclusions drawn. Please see Figs.1-4 and Supplementary Figs. 1-19.

2. The results presented on the "ACC velocity accelerates poleward during the LIG compared to that in the Holocene" are slightly disorganized and difficult to follow. Too much mention to the "Material and Methods" section is made, to the detriment of the readability and clarity of the paper. In order to improve this, I'd suggest to the authors to start the section with their comments on the location of the cores, and the validity of the sites for reconstructing the ACC, with a brief description of the basis of the chronology. No mention at all of the chronology is made in the main manuscript; a brief description here and a more extended explanation in the SOM is necessary. This could maybe introduce a quick discussion on sedimentation rates, the resolution of their SS analysis and why millennial-scale variability is not visible in these two cores (contrarily to the Drake Passage cores of Wu et al., (2021)[4] that the authors cite extensively).

Response:

Thank you for your insightful feedback on improving the clarity and organization of the section "ACC velocity accelerates poleward during the LIG compared to that in the Holocene." To address your concerns, we have reorganized our result to begin with a concise description of the core locations and their suitability for reconstructing ACC dynamics. We have also added a brief explanation of the chronology used in the main text following the reviewer's suggestion. A more detailed description of the chronology has been also included in the section on Materials and Methods. Please see lines 89-100 in the Main Text, and 611-635 in the Materials and Methods and Supplementary Figs. 1-2.

We have also included a discussion of sedimentation rates and the resolution of the sortable silt analysis, explaining why millennial-scale variability is not apparent in our cores, unlike the Drake Passage records of Wu et al. (2021)[4]. These revisions provide greater clarity and support for our findings, in line with your valuable suggestions. Please see lines 100-105 in the Main Text and Supplementary Fig. 3.

> 3. Then the text could move on to the chosen proxies and how they are pertinent in these locations and cores. For example, a quick discussion on the pertinence of $\overline{SS}$ vs $\overline{SSFS}$ at sites of high bottom current velocities would be appreciated. Could potential IRD values affect these records? The authors also mention that the southern and deeper core (at 59°S and 3713 m) is not significantly influenced by AABW (line 111), but this discussion is not developed or sufficiently argued. The reader is expected to know the paper of (Wu et al., 2021[4]), where a discussion on the depth and speed of modern ACC is developed in order to assess the validity of their core locations on the Drake Passage.

Response:

Thank you for your insightful comments regarding the chosen proxies and their pertinence to our study. To address your comments, we have added a discussion on the applicability of $\overline{SS}$ versus $\overline{SSFS}$, highlighting the suitability of $\overline{SS}$ at our cores. Additionally, we have also included an explanation of the potential IRD influence on our records, showing that its impact on the sortable silt signal is minimal at our study sites. Please see lines 116-141 in the Main Text.

To exclude the influence of AABW on our deeper core (U1537, 59°S, 3713 m), we have extended the discussion to include evidence from modern high-resolution ACC velocity data and dissolved oxygen concentrations with neutral density contours (γn) from the World Ocean Atlas 2013[15,16]. Additional supporting evidence, including Nd and Pb isotope records[17], grain size data[3,4,6], and apparent oxygen utilization[18-22], further demonstrates that ACC dynamics dominate at this site. Moreover, a more detailed explanation regarding the exclusion of AABW influence on this core is provided in the section of Materials and Methods. Please see lines 143-165 in the Main Text and lines 723-751 in the Materials and Methods, and Supplementary Figs. 9-12.

Finally, we have added a summary of key findings from Wu et al. (2021)[4] on the modern ACC's depth and speed, and compared them with our records to make it easier for readers to understand why we chose $\overline{SS}$ as the bottom flow speed proxy at our sites. We believe these revisions strengthen the manuscript and address your concerns effectively. Please see lines 121-131 in the Main Text.

4. A similar discussion for the cores of the Scotia Sea (whose differences with the Drake Passage are quickly highlighted in lines 83-84) would be welcomed. This section goes on describing the records and comparing them with nearby ones. The comparison with other locations is complicated for the reader, since there's no table or figure that presents all the cores and includes their depth. Just adding the names and depth of all the cores to the caption of Figure 1 will facilitate greatly the task. Although the authors go to lengths to compare their results to distal cores, one site highly-resolved, high-impact study seems to be missing from the discussion: the Pacific sector records of (Lamy et al., 2024)[5]. How do these results compare?

Response:

Thank you for your constructive and detailed feedback on this section. Following your suggestions, we have extended the discussion and included a similar comparison for the Scotia Sea cores with the Drake Passage cores, highlighting their differences and similarities. Please see lines 82-87, 116-131, 194-228 in the Main Text, Fig. 3 and Supplementary Fig. 14.

To facilitate comparisons and improve readability, we have updated the caption of Figure 1 to include the names and depths of all cores, making it easier for readers to understand the relationships between sites. Please see lines 835-838 in the Main Text.

Additionally, we have now included a comparison with the Pacific sector records from Lamy et al. (2024)[5] to enhance the discussion and provide a broader perspective on ACC dynamics in the Southern Ocean. We believe these revisions enhance the clarity and completeness of the manuscript. Please see lines 194-225 in the Main Text and Fig.3.

5. Two questions come to mind when comparing these very interesting records among themselves and with others: (1) Why are Holocene SS values in IODP Site U1537 so low? They are slightly higher than LGM values, but on the same level as MIS2 or MIS3, and half the values for the same period in IODP Site U1538, while LIG values are comparable. The three-fold increase in velocity during the LIG with respect to the Holocene at IODP Site U1537 is a direct result of this. (2) Why are the increases in current velocities at the LIG much higher in the Scotia Sea than in the Drake Passage? (alternatively, is this difference between the two regions statistically significant?). A discussion on these two points would be welcomed in this section, before the discussion of supporting evidence of lines 142-158.

Response:

Thank you for your thoughtful and insightful comments. Regarding your first question on the low Holocene $\overline{SS}$ values at IODP Site U1537, we fully agree with the reviewer that the significantly lower bottom flow speeds during the Holocene, which are approximately three times lower than those during the LIG and comparable to those during the LGM, MIS2, and MIS3, contrasts the conventional view of interglacial climatic similarity. To address the low Holocene $\overline{SS}$ values, we have investigated additional proxy data beyond the Scotia Sea to better understand the regional dynamics of the ACC. Notably, the reconstructed Holocene flow velocities from cores across the Drake Passage and Scotia Sea exhibited a similar pattern with modern observations[2], showing higher velocities around the PF and SAF and lower velocities south of the SACCF. ACC speeds during the LGM were lower relative to Holocene at multiple locations in the main fronts of the Drake Passage and the Scotia Sea, for example, decreased by 3.8 cm/s at Site PS97/093-2 (~40 km NW of the SAF, 3781 m)[3], 5.1 cm/s at Site PS97/085-3 (~40 km north of the PF, 3837 m)[4], and 4.4 cm/s at Site U1538 (SACCF) (Fig. r1a). This LGM decrease in ACC can be observed even in the central South Pacific[5]. However, the ACC velocities at Site U1537, located to the south of the SACCF in the Scotia Sea, were found to be low both in the LGM and the Holocene, and this relatively stable and low current velocities phenomenon had been reported previously in the Scotia Sea[6]. The above compilation suggests that the ACC intensity reduced considerably during the LGM, while the course configuration of the ACC front in the Scotia Sea and the Drake Passage remained relatively unchanged. This interpretation is supported by similar glacial and Holocene planktonic foraminiferal $\delta^{18}O$ distributions observed in both the Atlantic and Pacific sectors of the Southern Ocean[7]. Please see lines 194-213 in the Main Text, Fig. 3 and Supplementary Fig. 14.

For your second question regarding the larger velocity increases during the LIG in the Scotia Sea compared to the Drake Passage, we attribute this to regional differences in

ACC dynamics and interactions with local topography. During the LIG, the magnified ACC velocity with increasing latitudes, particularly pronounced at the southernmost stations during the LIG, indicates the ACC acceleration and poleward shift. Utilizing our new grain size data and previously published records, we infer that PF in the Scotia Sea shifted poleward by ~5°. A ~5° southward migration of the PF likely shifted the primary high-velocity zones further south. In the Scotia Sea, this allowed for significantly stronger flow in regions south of the modern PF. Yet, in the narrow Drake Passage, these changes likely imposed greater constraints on flow acceleration, contributing to relatively modest increases in current speed compared to the Scotia Sea. Please see lines 215-254 in the Main Text, Fig.3 and Supplementary Figs. 14-16.

6. The discussion in the section "Potential impact of ACC frontal changes on polar upper nutrient supply" needs rearranging and some additional explanations. The premise of the discussion seems to be already that eccentricity and precession are responsible for the changes seen in both records (lines 211-214), instead of being the conclusion based on a reasoned discussion. The records the authors compare their SS to in Fig. 4e do seem to be globally in agreement, but no explanation is offered about the offset that seems to occur around 70-80 ky, that is also evident with respect to precession. This whole section needs to be made clear, specially since it presents the main conclusion highlighted in the title and the abstract of the manuscript.

Response:

Thank you for your insightful comment. We have carefully reorganized the discussion section and provided clearer explanations. Specifically, we have now presented eccentricity and precession as conclusions derived from our analysis rather than as initial assumptions. Specially, we have rearranged the section to first establish the temporal and periodic patterns in $\overline{SS}$ records, showing that the low-frequency variability of U1537 $\overline{SS}$ aligns with eccentricity, and high-frequency cycles with precession, through time-series analysis (e.g., by wavelet and spectral analysis). Then we have further investigated this phenomenon globally by examining the ACC record from Site MD00-2375G, located north of the SAF. Additionally, we have explored potential underlying mechanisms, including the modulation of Southern Hemisphere Westerlies by orbital precession, which is further amplified by variations in orbital eccentricity, influencing ACC front movement. Furthermore, we have strengthened our conclusions by integrating global paleoclimate datasets (e.g., Southern Hemisphere westerlies and Intertropical Convergence Zone records) with orbital parameters. This revised structure provides a more robust basis for concluding that orbital eccentricity and precession influenced ACC frontal dynamics through their effects on the Southern Hemisphere westerlies and surface ocean conditions. Please see lines 260-296 in the Main Text.

To address the offset observed around 70-80 ka, we have added an explanation in the revised manuscript. This offset is consistent with increased Antarctic temperatures (Fig. r6), likely reflecting a response of ACC to regional influence, rather than orbital forcing. However, further research is required to fully understand these processes and their interactions. Please see lines 296-303 in the Main Text and Fig. r6.

We have also enhanced the clarity and strengthened the connections between the ACC front, Southern Hemisphere westerlies, orbital forcing mechanisms, and their implications for the Antarctic Ice sheet, polar nutrient supply, as well as atmospheric CO_2 concentrations, ensuring a more robust and cohesive presentation of the findings. Please see lines 306-332 in the Main Text.

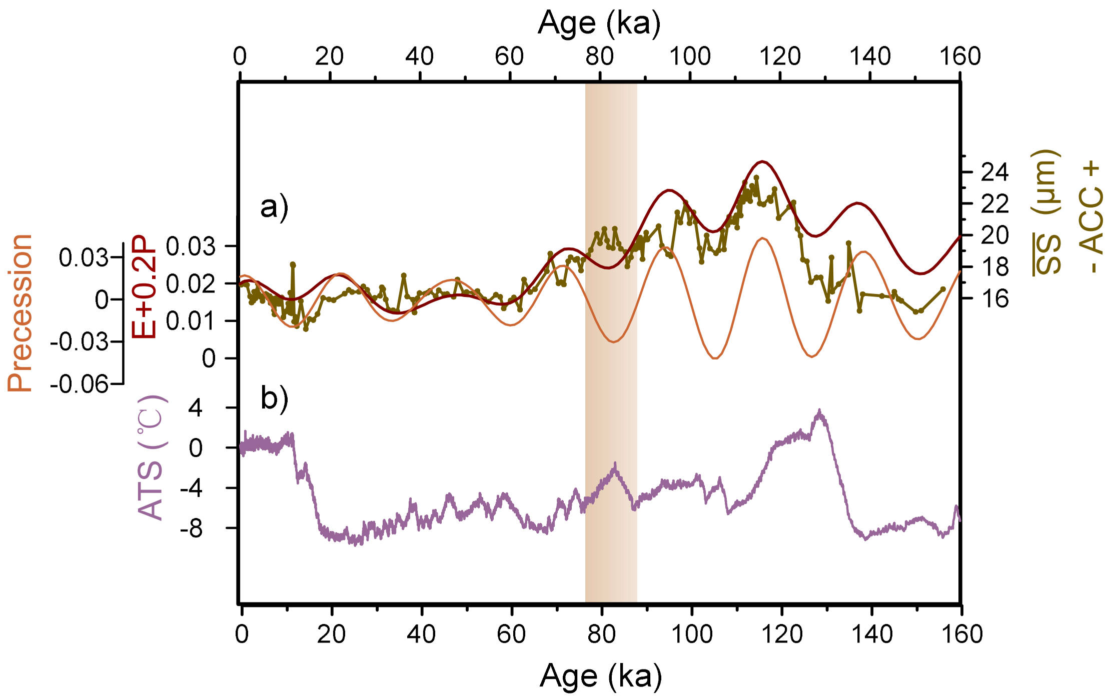

Fig. r6 | Comparision of grain size at Site U1537 with orbital parameters and Antarctic Temperature. a) Eccentricity (E)+0.2 precession (P)[12], precession[12] and $\overline{SS}$ at Site U1537; **b)** Antarcitc temperature stack[1].

Minor comments:

7. Fig. 1: it is difficult to see the difference between colors indicating depth and speed of surface currents. A list in the caption of names and depths of cores attached to the 1 to 12 numbers in the right figure would be useful. Please add latitudes to the blown-up location map.

Response:

Thank you for your insightful suggestion regarding Fig. 1. Based on your valuable feedback, we have made several revisions to improve its clarity and utility. Specifically, we have adjusted the colors to enhance the visibility of surface current speeds. To facilitate interpretation, we have added a list of core names and depths corresponding to numbers 1 to 12 in the right panel, now included in the figure caption. Furthermore, latitudes have been added to the enlarged location map to provide additional geographic context. We believe these adjustments significantly enhance the figure's readability, making it easier for readers to follow the relationships between core locations and oceanographic parameters. Please see lines 835-838 in the Main Text and Fig.1.

8. Fig. 4: Please explain your choice of eccentricity+0.2precession. Power in the precession band is very low for 1387.

Response:

We thank the reviewer's valuable comment. We have added an explanation regarding the combination use of eccentricity+0.2 precession. Specifically, we selected this combination as a simplified representation of orbital forcing impacts. To quantify their relative contributions, we conducted several combination tests (Fig. r7). We found that the combination eccentricity + 0.2 precession aligns best with our records (Fig. r7c), providing a reasonable approximation for their joint influence. Therefore, we adopted this approach in our analysis.

Regarding the low precession signal at U1537 in Fig.4, its robustness is supported by its strength exceeding the 80% confidence level. This is further reinforced by wavelet analysis, which consistently reveals a pronounced precession signal. Moreover, our records align best with the combination of eccentricity and 0.2 precession (Fig. r7c), further corroborating the reliability of the precession signal. Please see Fig.4, Supplementary Figs. 17-18.

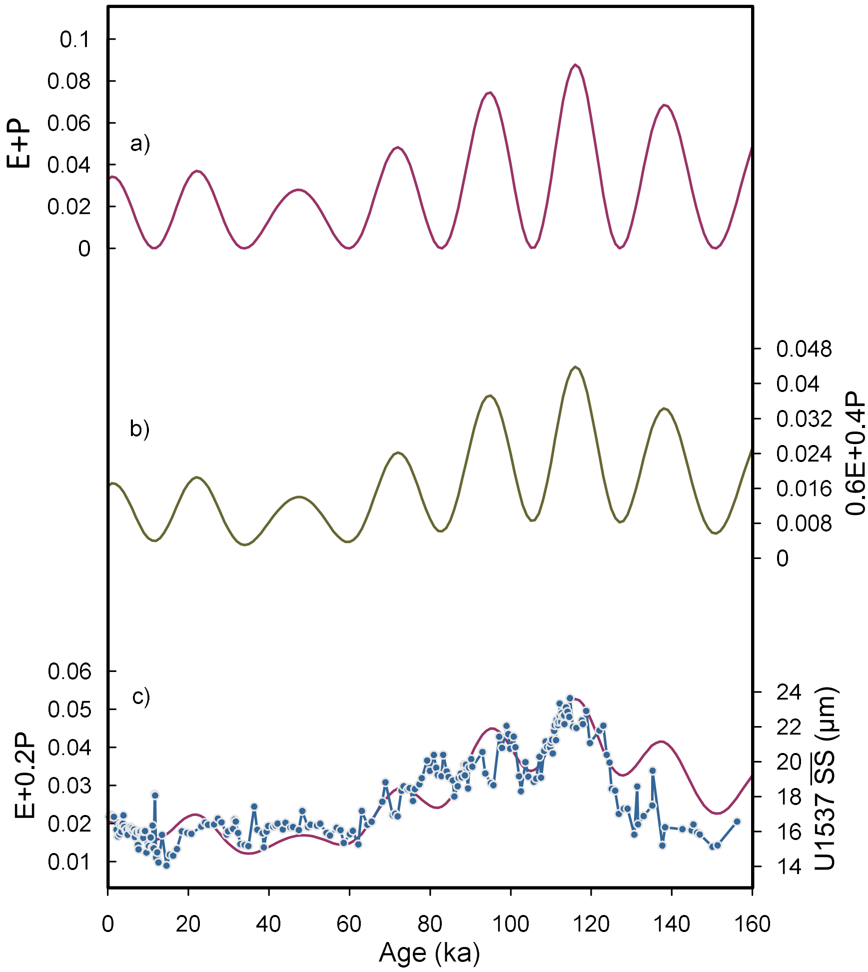

Fig. r7 | Comparision of grain size at Site U1537 with orbital parameters. a) Eccentricity (E)+ precession (P) [12]; **b)** 0.6E+ 0.4P[12]; **c)** E+ 0.2P and $\overline{\mathrm{SS}}$ at Site U1537.

9. Extended data Fig. 4e: units missing.

Response:

We have added the missing units to Supplementary Fig. 4e in the revised manuscript. Please see Supplementary Fig. 4e in the Main Text and Fig. r8 in this document.

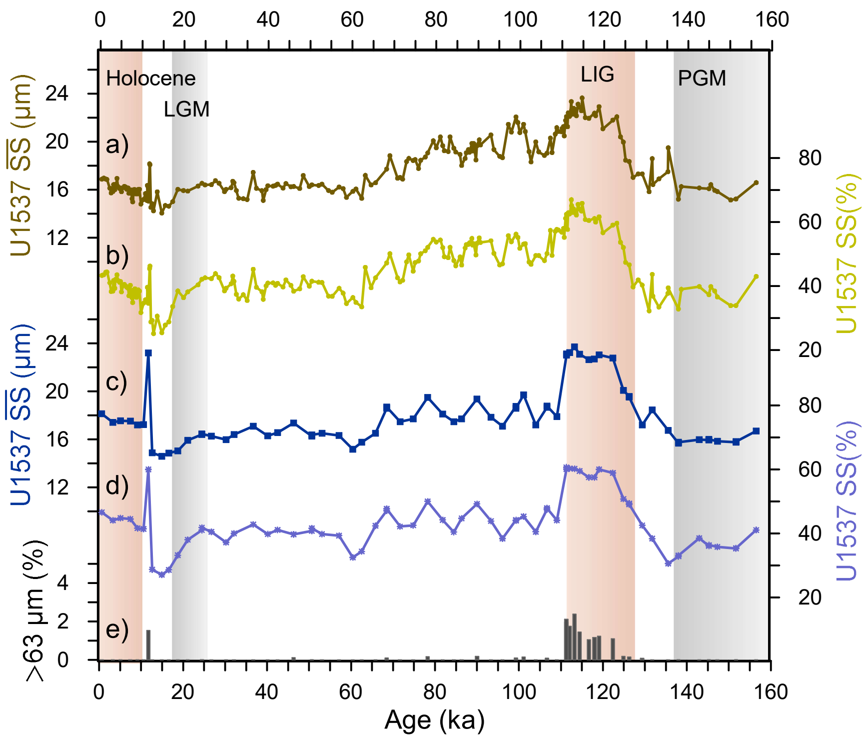

Fig. r8 | Results of grain-size measurements at Site U1537. a) and **b)** are $\overline{SS}$ and SS% in Group One of U1537, respectively. **c)** and **d)** are $\overline{SS}$ and SS% in Group Two of U1537, respectively. **e)** The percentage of grain size larger than 63 µm in Group Two of U1537; LGM = Last Glacial Maximum; PGM = Penultimate Glacial Maximum.

10. Extended data Fig. 15: the region of high power shows mainly btw 100-120 ky, and not during 60-100 ky, which supports my previous comment that precession does not affect the whole record equally.

Response:

Thank you for your observation in Extended Data Fig. 15 (Supplementary Fig. 17 in the revised manuscript). We agree that the high-power region between 100-120 ka reflects a stronger precessional influence, while the lower power during 60-100 ka suggests precession did not affect the record uniformly, likely due to regional climatic factors such as increased Antarctic temperatures. We have clarified this in the revised manuscript. Please see lines 298-303 in the Main Text and Supplementary Fig. 17, Fig. r6.

Reviewer #3 (Comments to Author (shown to authors):

1. The authors reconstruct the Antarctic Circumpolar Current (ACC) in both speed and location back to 160 ka. This dataset is novel and important for understanding past climates and is a valuable contribution to the literature. The observed connection between these currents and orbital parameters is fascinating and worthy of further study. I especially value the distincton and discussion regarding both the ACC and the Southern Hemisphere Westerlies (SHW). I have some comments that will both help to clarify these results and give them more context within existing literature. Strengthening the argument through more explicit numbers and references in the text will be beneficial.

Response:

Thank you for your encouraging feedback and thoughtful suggestions. We deeply appreciate your recognition of the significance of our findings, particularly regarding the ACC, orbital parameters, and the Southern Hemisphere Westerlies. To address your comments, we have incorporated explicit numerical details into the discussion and provided clearer evidence supporting our conclusions. Additionally, we have included more context from relevant literature and cited references suggested by the reviewer to enhance the robustness and clarity of our arguments. We believe these revisions improve the overall quality of the manuscript. Please see lines 260-303 and 317-332 in the Main Text.

2. I would explicitly say which direction the isopycnals are tilted in the sentence on lines 59-62.

Response:

We sincerely thank the reviewer for their insightful comment. To address this, we have clarified the direction of the isopycnal tilt in the revised manuscript as follows: "Its isopycnal surfaces tilt meridionally from the upper ocean to deeper waters, establishing strong linkages between the surface ocean and nutrient- and CO_2-enriched deep water. This dynamic enhances the nutrient supply for biological productivity and facilitates the air-sea CO_2 exchange." Please see lines 58-62 in the Main Text.

3. The discussion of precession's influence on the SHW could use more explanation and clarity. For example, the lines 183-185 "Due to the perihelion occurring in the southern hemisphere, the Antarctic region receives elevated solar insolation during summer." need to be clarified. Do you mean that the perihelion occurs during the southern hemisphere summer? It is also important to make a distinction between boreal (NH) and austral (SH) summer. A similar clarification needs to be made for lines 180-181.

Response:

We sincerely thank the reviewer for their careful review and thoughtful comments. To address your concerns, we have clarified the description of precession's influence on the Southern Hemisphere Westerlies to improve both precision and clarity. For example, we have revised the sentence as below: "Particularly during the LIG, when orbital eccentricity and precession reached their maxima, with perihelion occurring during Southern Hemisphere summer, the resulting maximum Southern Hemisphere insolation coupled with reduced Northern Hemisphere insolation likely intensified interhemispheric temperature gradients. This enhanced meridional temperature gradient would intensify SHW shifts, driving the ACC to the southernmost position." Please see lines 283-287 in the Main Text.

4. Line 192 - Define what a precession maxima is since it is not consistent between papers. This could be done in correction made to my previous suggestion.

Response:

To improve clarity, we have defined a precession maximum as when the orbital precession amplitude reaches its highest value. Please see lines 265-268 in the Main Text.

5. Line 197 change "As the precession could alter" to "As orbital precession alters" since that is objectively what precession does.

Response:

We have rewritten the sentence according to your helpful suggestions. Please see lines 275-287 in the Main Text.

6. There are some modelling studies that you can reference to support your finding that orbital precession alters the strength and position of the SHW. Adding these citations will strengthen your results.
- Rutgers 2019 "Response of the High-Latitude Southern Hemisphere to Precessional Forcing: Implications for Pleistocene Ocean Circulation" finds that a high precession index causes the SHW shift poleward and intensify using GFDL.
- Persch 2023 "The Impact of Orbital Precession on Air-Sea CO_2 Exchange in the Southern Ocean" also finds that a high precession index causes the SHW shift poleward and intensify using CESM.

Response:

Thank you for this valuable suggestion and for pointing out these relevant studies. We have incorporated the references to Rutgers et al. (2019)[23] and Persch et al. (2023)[24] to strengthen our finding that orbital precession influences both the strength and position of the Southern Hemisphere Westerlies following your suggestion. Please lines 275-277 and 319-328 in the Main Text.

7. The discussion in the lines 228-233 could use some numbers. My instinct is that the rate of change expected due to changing orbital parameters is significantly lower than the one being observed due to anthropogenic forcing, but that may not be the case. I think providing these rates would help clarify how much counterbalancing is to be expected.

Response:

We sincerely thank the reviewer for raising this critical point regarding comparative forcing rates. We fully recognize that quantifying orbital versus anthropogenic climate impacts is critical. However, relying on our limited regional proxy data makes it challenging to quantitatively assess the rate of changes driven by orbital-scale forcing and anthropogenic forcing. Future research, involving detailed modeling studies or additional datasets, would be required to accurately quantify orbital forcing rates. Therefore, in the updated version, we have focused more on the discussion of the changes in the position of the ACC front driven by orbital parameters and of the potential orbital-driven trend of ACC in the future. Please lines 334-341 in the Main Text.

8. Some numbers pulled from Figure 4 would help back up the claim you make in lines 202-203 that eccentricity is primary and precession is secondary.

Response:

Thank you for your insightful comment. We have extracted specific numerical values from Fig. 4 to quantitatively demonstrate the dominance of eccentricity as the primary driver and precession as the secondary influence. Please see Fig. 4 and lines 293-296 in the Main Text.

9. The sentence in lines 205-206 is not a complete sentence. Adding "it is" at the beginning would fix this.

Response:

We have added “it is” at the beginning of the sentence in lines 205-206, as suggested, to ensure the sentence is complete. Please lines 296-298 in the Main Text.

10. I think the discussion would benefit from drawing a connection between the observed changes in SHW and atmospheric CO_2. This could be brought up as a secondary feature relative to the ACC changes, but there are many modelling studies that have sought to address this (d’Orgeville et al., 2010[25]; Menviel et al., 2008[26]; Tschumi et al., 2008[27]).

Response:

Thank you for this valuable suggestion. We have expanded the discussion to include the connection between Southern Hemisphere Westerlies variability, ACC changes, and atmospheric CO_2, supported by relevant modeling studies (d’Orgeville et al., 2010[25]; Menviel et al., 2008[26]; Tschumi et al., 2008[27]). These studies demonstrate that shifts in Southern Hemisphere Westerlies modulated the position and strength of the ACC, which impacted CO_2 exchange in the Southern Ocean, providing a key mechanism for atmospheric CO_2 variability. Please see Fig. 4 and lines 317-332 in the Main Text.

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Point-by-point response to reviewers' comments

Reviewer #1 (Comments to Author (shown to authors):

I would like to thank the authors for going through all the reviewer comments and substantially revising the manuscript. As I will detail below, I still have a major concern that I would like to see addressed before publication.

Response:

We sincerely appreciate the reviewer's constructive feedback. We have provided expanded discussions to comprehensively address the remaining concerns raised by the reviewer in this revised manuscript. We believe this version meets the Nature Communications publication standard.

Main concern:

2. I still find the analysis and/or presentation of the LIG to Holocene ACC changes and associated frontal positions difficult to follow and not always convincing. Perhaps I should have articulated that point more clearly in the previous round of review, although both reviewers 1 and 2 commented on it and it hasn't substantially improved.

To me, the main figures of the manuscript are 3i and 3j, they attempt to directly provide insigh into the differences between LIG and Holocene flow speeds across the ACC and possible latitudinal shifts.

Figure 3i shows the 'modern' relationship between flow speeds and Holocene reconstructed flow speeds. On lines 199-201 the authors say that they show a similar pattern. But do they really? Can one see the maxima and minima of observed flow speeds reflected in the reconstructions? Could one deduce the positions of the different fronts based on the Holocene reconstructions of flow speeds? If one plots the two measures of flow speed against each other, does one get a significant relationship?

Figure 3j is the figure that should show the reader the latitudinal migration of the ACC and assosiated fronts. The authors explain in their respons that they only show data for two cores for the LIG in figures 3i and 3j to 'provide a clearer and more region-specific understanding of front migration'. I would argue that reconstructing changes in a complex system of several fronts and several related flow speed maxima and minima, cannot be done on information from two cores alone (two cores that are also very close together so they do not add much information apart from showing that the signal is robust for that small region). Clearly the authors provide all kinds of other pieces of evidence, like sortable silt changes in other regions of the ACC, temperature changes and d13C changes. This is also shown in figure 3a, with various sorts of red arrows. But still, like the data is currently presented, the reader mostly just has to believe that taking all this data together one finds support for a southward migration of the ACC during the LIG. I think that the authors should find a way to combine all the data into a more convincing figure. Perhaps a way to combine all cores into a figure like 3j would be to make the x-axis into an axis that lumps together all sediment core information anywhere along the ACC between front a and b; between front b and c etc?

Another thing that could help is if the arrows in figure 3a are already 'translated' by the authors from temperature, sortable silt, d13C etc, into latitudinal shifts of the ACC. Clearly that comes with some assumptions as non of those records are proxies for 'latitudinal shifts of the ACC', but that would allow the reader to visually follow the line of reasoning of the authors as described at length in the main text.

Response:

We sincerely thank the reviewer's constructive feedback, which has helped us significantly improve the presentation and interpretation of the Last Interglacial (LIG) to Holocene Antarctic Circumpolar Current (ACC) changes and associated frontal positions. We agree with the reviewer that the modern flow velocity pattern observed in the Drake Passage (Jason Track 104) in Figure 3i differs from the reconstructed Holocene flow velocities in the Scotia Sea. We attribute this discrepancy to two main factors: 1) regional heterogeneity in flow velocity variations between the Drake Passage (Jason Track 104 observations[1]) and the Scotia Sea, and 2) timescale differences between reconstructed current and observed flow speed. Specifically, the Jason Track 104 velocity measurements capture inter-annual to sub-annual variability influenced by mesoscale eddies and jets, exhibiting high-frequency fluctuations, whereas the ACC Holocene flow velocities reconstructed from Scotia Sea sediment cores reflect centennial-to-millennial mean-state trends. To minimize regional biases in modern observations, we selected satellite altimetry-derived velocity data (Global Ocean Gridded L4 Sea Surface Heights And Derived Variables Reprocessed Copernicus Climate Service) from the Scotia Sea[2] (spatially consistent with our sediment cores) instead of Drake Passage data. By extracting the trend component, we derived the mean-state ACC variability, revealing a modern north-strong/south-weak velocity trend

(Fig. r1). This approach demonstrates statistically significant Pearson correlations (r = 0.72, p = 0.01) between modern and Holocene flow speeds (Fig. r1), robustly validating our reconstruction's capability to capture the ACC's frontal structure dynamics. Please see lines 197-219 in Main Text and Fig.3h.

According to the reviewer's suggestions, we integrated our two records with published records of sortable silt, ARM/k, sea surface temperature (SST), and planktonic foraminifera records from 7 sediment cores spanning the ACC's frontal zones (Subtropical Front (STF) to Southern ACC Front (SACCF)) into a more convincing figure to support for a southward migration of the ACC during the LIG. To enable direct comparison, we normalized proxy values as (LIG-Holocene)/Holocene, highlighting relative changes across latitudes (Fig. r2). The compiled figure exhibits that LIG flow speeds increased progressively southward, with a moderate decrease near the STF (-28.3% at Site MD00-2375G[3]), a minor increase near Subantarctic Front (SAF, 5.5% at Site PS97/093-2[4]), a moderate increase near the Polar Front (PF, 8.4% at Site PS97/085-3)[5], but dramatic increases at the SACCF (58.3% at Site U1538), and to southern SACCF (211.0% at Site U1537). This pattern suggests frontal poleward migration, as uniform transport increases would not explain such spatial heterogeneity.

Moreover, SST warming at Site PS75/034-2[6] (SE Pacific) during the LIG aligns with a southward-displaced SAF, allowing warmer waters to influence this region. Southward Subtropical Convergence (STC) shift in the Cape Basin[7] (planktonic foraminifera records) independently corroborates large-scale ACC displacement. The new composite figure (Fig. r2) integrates all proxies into a single latitudinal framework, explicitly linking flow speed changes to frontal shifts. Please see Fig. 3i.

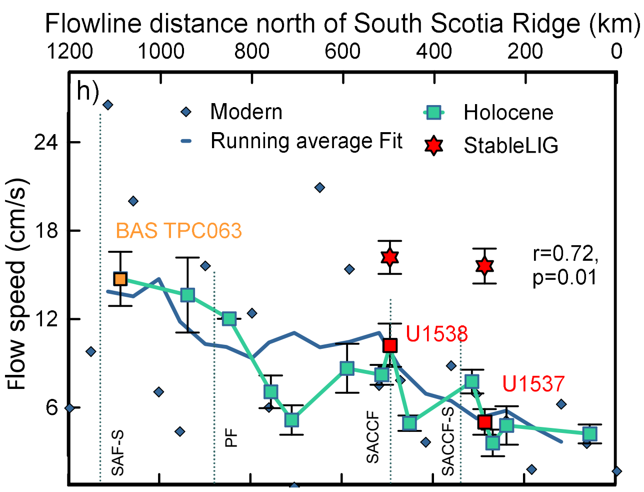

Fig. r1 (new Fig. 3h of the revised manuscript) | Comparison of modern current speed from the satellite data[2] and the Holocene across the transect of the Scotia Sea. Holocene average values are shown as blue squares (except U1537 and U1538 in red, BAS TPC063 in orange), and Stable LIG values are shown as red stars, with error bars indicating one standard deviation.

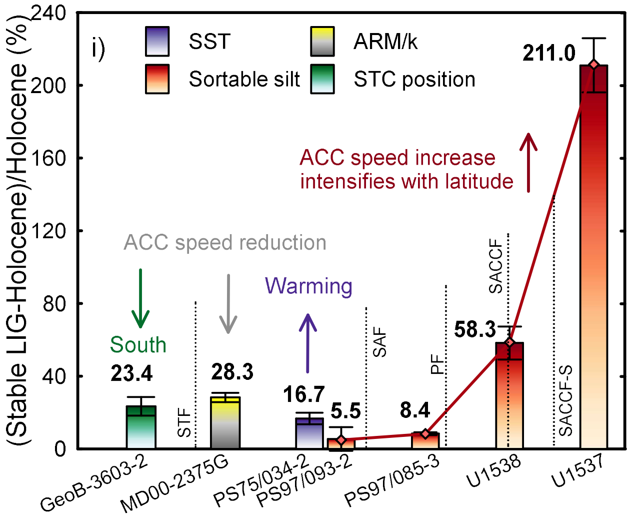

Fig. r2 (new Fig. 3i of the revised manuscript) | Comparison of current speed[3,4,5], sea surface temperature[6], and other proxies across the front during the LIG. The plotted values represent the relative percent change between Stable LIG and Holocene, with error bars showing the estimated uncertainty of the relative difference.

Minor comments:

1. Lines 79-80: "which has profound implications for projecting their future interactions within the dynamic ice-ocean-climate system". Given that the authors show that the ACC seems mostly driven by long-term changes in eccentricity and precession, not global temperatures, I find the statement that the results of this study have profound implications for projecting future ACC changes, too strong a statement. Perhaps the authors mean with 'future' the future on orbital time-scales, but this is not sufficiently clear given that the paragraph starts with a discussion on present-day and future (IPCC-timescale). Please adjust.

Response:

We sincerely thank the reviewer for the insightful comments. We have clarified the sentence. The revised sentence now reads: "Here, we aim to elucidate the natural forcing for the configuration and reorganization of the ACC frontal systems at orbital timescales, which has profound implications for ACC variability and its interactions with the ocean-atmosphere-cryosphere systems”. Please see lines 76-78 in Main Text.

2. Line 167: “highly likely” seems really too stronge a statement here

Response:

Thank you for pointing this out. We have carefully revised the sentence as follows: “Given the latitudinal difference between Site U1537 and Site BAS TPC063, it can be inferred that the PF in the Scotia Sea may have shifted poleward by ~5°”. Please see lines lines 273-275 in Main Text.

3. Line 192: the specific mention of ‘Antarctic air temperature’ seems a bit odd here. I understand that the ice core data is providing this information, but to the reader it would seem strange that ACC dynamics are only compared to Antarctic air temperatures and not, for instance, Southern Ocean sea-surface temperatures. Please clarify in the text.

Response:

We sincerely appreciate your insightful comment. We have included a comparison with Southern Ocean sea-surface temperatures and revised the sentence to incorporate this comparison, as follows: “Although both the Southern Ocean sea surface temperatures and Antarctic air temperatures exhibit typical interglacial climactic features, i.e., similar temperature conditions during the LIG and the Holocene, our records reveal a significant contrast in the hydrological behavior of the ACC between these two periods.” Please see lines 191-195 in Main Text.

Technical comments:

1. Line 171: words missing at the end of this line.

Response:

Thank you for your careful review. We have corrected the missing words at the end of line 171. The revised sentence is: “The $\overline{SS}$ record at Site U1537 located south of SACCF is relatively low during the Penultimate Glacial Maximum (PGM, 158-135 ka), with an average $\overline{SS}$ of 16.3±1.2 μm. Please see lines 171-173 in Main Text.

Reviewer #2 (Comments to Author (shown to authors):

1. I have appreciated the effort that Lu and coauthors have done in responding to the comments, the rebuttal letter is very complete. In particular, the effort in rearranging the results and the discussion sections has made them much more complete, and they now present a clear logical development directed at supporting their conclusions. The manuscript is now easier to read and more coherent.

Response:

Thank you very much for your recognition of our effort. We greatly appreciate your constructive feedback, particularly on the results and discussion sections, and we have carefully addressed them in the current revised version.

2. However, I do still feel that an explanation for the very low values of SS during the Holocene in site U1537 is still not offered, other than a (insufficient) mention to a "decoupling of Antarctic air temperature and ACC" (line 192), presumably during the Holocene. There's a more extended paragraph in the rebuttal letter, but I am afraid I do not quite grasp the explanation.

Response:

We sincerely thank the reviewer for raising this important point regarding the low Holocene $\overline{SS}$ values at Site U1537. We have provided clearer and more adequate explanations in this revised manuscript.

1) Modern Oceanographic Context: According to the velocity profile from the Scotia Sea (Fig. r1), Site U1537, located south of the SACCF, exhibits significantly lower flow velocities compared to the ACC's main stream (PF and SAF). This aligns with our reconstructed Holocene $\overline{SS}$ values from the Scotia Sea. Moreover, the high correlation between reconstructed Holocene velocity and satellite altimetry-derived velocity data (spatially consistent with our sediment cores) (Pearson $r = 0.72$, $p = 0.01$; see Fig. r1) supports the robustness of our interpretation. Please see lines 197-219 in Main Text and Fig.3h.

2) Orbital-Scale Forcing and Front Stability: Given the strong correlation between reconstructed flow velocities at U1537 and eccentricity over the past 160 ka, we infer that the low flow speeds (low values of $\overline{SS}$) during the Holocene at the U1537 were associated with low eccentricity and the relatively northerly position of the ACC. During the Holocene, low eccentricity led to overall weaker seasonal insolation and smaller inter-hemispheric temperature gradients, which likely contributed to a northward displacement of the SHW. This kept the SACCF and the PF persistently north of Site U1537, thereby maintaining the region — similar to present-day conditions—in a low-velocity regime. In contrast, during the LIG, high eccentricity combined with high precession effects lead to large inter-hemispheric temperature gradients and shift the SHW southward, driving an approximately 5° poleward migration of the ACC. Consequently, a significant increase in flow speed (triple times the Holocene velocity) was observed even at the southern location of Site U1537 and U1538. Please see lines 308-318 in Main Text and Fig.3h.

3. In lines 245-246 it is stated that their Holocene SS-derived current velocity is "consistent with contemporary current distribution". However, if I understand correctly their figure 3i, the Holocene values in U1538 should be lower than those in U1537 in order to be consistent with the geostrophic velocities along Jason Track 104 (green line). (Could the different patterns between Holocene-LGM and LIG-PGM between U1538 and U1537 be also the result to the differences in eccentricity?).

Response:

We would like to thank the reviewers for raising this issue and apologize for our inaccurate statement in the initial presentation. As noted by the reviewers, there is indeed an inconsistency between the velocity observations from the Jason Track 104 across the Drake Passage and our Holocene velocity reconstructions from the Scotia Sea. Specifically, the Jason 104 velocity profile across the Drake Passage exhibits multiple peaks and troughs, while the Holocene reconstructions from the Scotia Sea display a trend of "stronger in the north and weaker in the south". Furthermore, based on the observations from the Jason 104 profile, the velocity at Site U1537 should be higher than that at U1538; however, our Scotia Sea reconstruction indicates that U1538 > U1537. This divergence arises fundamentally from regional ACC heterogeneity and temporal scale differences.

1) The regional heterogeneity of the ACC velocity structure between the Scotia Sea and the Drake Passage: The ACC in the Drake Passage is strongly constrained by its narrow and complex topography, resulting in a velocity profile that often shows multiple peaks and troughs. In contrast, the Scotia Sea, located downstream of the Drake Passage, has

a significantly broadened ACC flow, which is more responsive to the latitudinal migration of the Southern Hemisphere westerlies, leading to a velocity profile that exhibits the trend of “stronger in the north and weaker in the south”.

2) The temporal scale differences between modern circulation observations and Holocene circulation reconstructions: The Jason profile across the Drake Passage captures interannual to sub-annual high-frequency fluctuations, including mesoscale eddies and jets[8]. In contrast, the Holocene ACC velocity reconstructions based on sediment core data from the Scotia Sea reflect centennial-scale mean-state trend.

To minimize regional biases in modern observations and validate our reconstruction results, we employed satellite altimetry-derived velocity data from the Scotia Sea – spatially aligned with our core locations – rather than velocity data observed for the Drake Passage. By extracting trend components, we obtained the modern mean flow field of the ACC. This flow field clearly illustrates the “stronger in the north and weaker in the south” velocity pattern (U1538 > U1537), which is entirely consistent with our circulation reconstruction results. Importantly, this method demonstrates a significant Pearson correlation ($r = 0.72$, $p = 0.01$; Fig. r2) between modern average velocities and Holocene reconstruction values, strongly validating our ability to reconstruct the dynamics of the ACC front structure. Please see lines 204-219 in Main Text and Fig.3h.

Regarding divergent Holocene-LGM and LIG-PGM velocity patterns at U1538/U1537, we attribute these fundamentally to orbital eccentricity-driven ACC shifts. During periods of high eccentricity (e.g., the Last Interglacial), an enhanced interhemispheric temperature gradient drives the southward migration of the Southern Hemisphere westerlies, leading to a southward shift of the ACC and resulting in synchronous acceleration of velocities at both U1537 (located further south) and U1538, with a more pronounced increase at U1537. Conversely, during periods of low eccentricity (e.g., the Holocene), the northward shift of the SACC) causes a reduction in velocity at U1537, while U1538 remains influenced by the stable core region of the SACCF. We have elaborated on the mechanisms linking eccentricity with the spatiotemporal response patterns of the ACC in the main text (lines 284-318).

4. Abstract: in view of the anomalous very low values of the Holocene in one of the cores, the statement about the three-fold increase during LIG with respect to it seems rather not the main point. The conclusion of a southward shift of the ACC of around 5 degrees is important enough!

Response:

Thank you for your constructive comment. We agree that a southward shift of the ACC of around 5 degrees is the main point in our abstract. We have revised the abstract to emphasize this key finding. Please see lines 48-50 in Main Text.

5. Lines 143-168: The low influence of AABW on the study sites is not quite well proved (although in all fairness, maybe it cannot be proved). Comparison with MD07-3076Q is used to prove that AABW is not influencing U1538 or U1537; however, this eastern South Atlantic record shows very detailed millennial-scale variability that, as the authors acknowledge, cannot be well recorded in their sites due to the sampling resolution. Also, the comparison between U1537 and PS1768-8 is used as proof of a different Holocene-LIG behaviour (thus not showing AABW); if we were to compare PS1768-8 with U1538, would the conclusions be different, seeing the higher SS Holocene values in this core? Could this be related to the different Holocene behaviour between U1537 and U1538? (i.e., an AABW influence during the Holocene in U1537, that it doesn't happen during the LIG?).

Response:

We thank the reviewer for the comments regarding the influence of AABW at our study sites. We acknowledge the challenges in completely excluding its influence. However, based on available evidence, AABW likely exerts only a minor influence at both sites and is not the dominant control. First, $\overline{SS}$ values at both Sites U1537 and U1538 peak during the LIG but remain low in the Holocene. In contrast, core PS1768-8 records show stronger AABW during the Holocene and weaker activity during the LIG[9]. This discrepancy argues against AABW being the primary control. Even if AABW influenced U1537 $\overline{SS}$ during the Holocene, its effects would be small given the low flow velocities recorded at both U1537 and U1538 during this period. Second, although the resolutions at Sites U1537 and U1538 are relatively low and may not fully resolve millennial-scale variability comparable to that in core MD07-3076Q, neither site shows clear evidence of enhanced Heinrich Stadials in $\overline{SS}$ variations on millennial timescales, as observed in MD07-3076Q[10,11,12,13,14]. This further indicates that AABW is not the dominant driver of dynamic changes at these two sites. Please see lines 149-165 in Main Text.

6. Line 171-192 and elsewhere: the uncertainties of the calculations are not shown. Even a simple standard deviation for the average values would be useful, to be able to compare different cores/periods and see if they are statistically significant or not.

Response:

Thank you for your helpful comment. We have now added the uncertainties of the calculations, including the standard deviation (σ) for the average values in the revised manuscript. Moreover, we have added the standard error of the mean (2σ/√n) and the analytical precision of ± 0.08 μm in our measurements in Supplementary Table 2 and the related caption. Please see lines 171-186 in Main Text and the Supplementary Table 2.

Table 1 (Supplementary Table 2 of the revised manuscript). The results of grain size measurements at Sites U1537 and U1538

Number	Sites		Holocene	σ	2σ/√n	LGM	σ	2σ/√n	LIG	σ	2σ/√n	PGM	σ	2σ/√n
1	U1537(1)	Average $\overline{SS}$ (μm)	16.1	0.5	0.2	16.2	0.3	0.3	21.5	1.8	0.8	16.3	1.2	0.7
2	U1537(2)	Average $\overline{SS}$ (μm)	17.6	0.3	0.3	16.3	0.2	0.3	21.7	1.5	1.2	16.0	0.4	0.2
3	U1538	Average $\overline{SS}$ (μm)	19.0	0.8	0.5	16.6	0.3	0.4	21.5	1.6	1.1	17.8	1.2	0.8

Note that the analytical precision was ± 0.08 μm in our measurements. It is not additionally propagated into the standard error of the mean, 2σ/√n. U1537(1) = Group One of U1537; U1537(2) = Group Two of U1537.

7. Line 192: suggest the decoupling of Antarctic air temperature and ACC when? During the Holocene or during the LIG?

Response:

Thank you for your comment. We have revised the sentence, which now reads: "Although both the Southern Ocean sea surface temperatures and Antarctic air temperatures exhibit typical interglacial climactic features, i.e., similar temperature conditions during the LIG and the Holocene, our records reveal a significant contrast in the hydrological behavior of the ACC between these two periods.

Please see lines 191-195 in Main Text.

8. Line 211-213: The cited reference includes a compilation of cores at different latitudes, that are not necessarily applicable here. As their own data show, there's a Holocene-LGM difference in U1538, as in many other cores around the Southern Ocean, so I'm not sure it is the right study to cite.

Response:

We thank the reviewer for pointing this out. To avoid potential confusion, we have removed this reference from the revised manuscript to support our interpretation of Holocene-LGM changes.

9. Lines 225-226: the increase in ACC velocity during the LIG is interpreted as ACC acceleration and poleward shift. However, from here on, only the poleward shift is addressed. Could you explain why do you dismiss ACC acceleration? Can you estimate how much of the SS signal could be due to it? If there's enough ACC acceleration, you may not need to invoke a poleward shift to explain the data.

Response:

Thank you for your valuable comments. When interpreting the observed flow velocity changes during the LIG, we have considered the effects of both ACC acceleration (increased volume transport) and poleward shift mechanisms. If only ACC acceleration occurred, the reconstructed velocities across major fronts would be expected to exhibit broadly uniform enhancement. However, our compilation reveals a distinct latitudinal pattern: the magnitude of ACC velocity increase during the LIG relative to the Holocene amplifies progressively toward higher latitudes, peaking most prominently at Site U1537 located close to the ACC's southernmost boundary. This spatial gradient cannot be fully explained by ACC intensification alone, instead pointing compellingly to a poleward shift of ACC fronts during the LIG. Although limited LIG ACC reconstruction data preclude quantitative isolation of the relative contributions from acceleration versus frontal migration, the poleward shift interpretation is robustly reinforced by convergent lines of evidence from multiple independent proxies (sortable silt, ARM/k, SST, and planktonic foraminifera records). Please see lines 244-267 in Main Text.

10. Lines 260-273: Is this precessional variability also evident in U1538?

Response:

Thank you for your insightful question. Yes, as shown in Fig. r3-r4, precessional variability is also identifiable at Site U1538. Please see Supplementary Figs. 16-17.

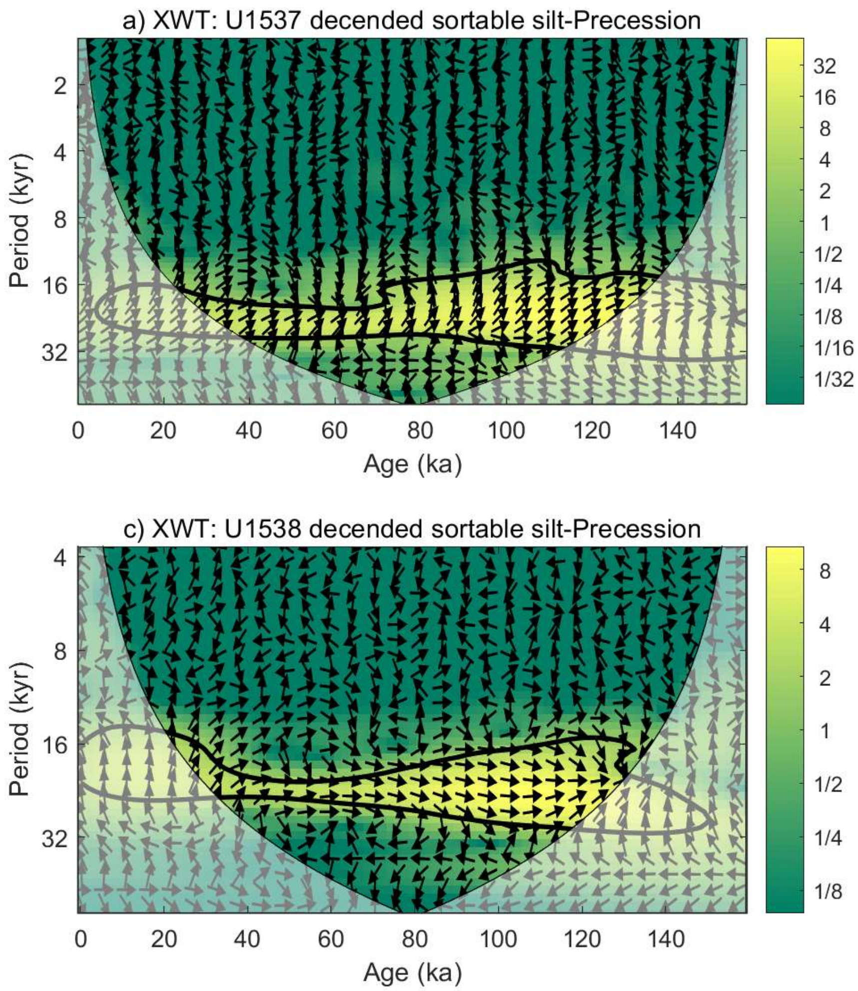

Fig. r3 | Cross-wavelet transform (XWT) spectrum of detrended $\overline{SS}$ and precession index[15]. The black thick line of statistical significance designates the 95% confidence level against red noise. The right color bar indicates the power. The phase relationship is indicated by the arrows, with right arrows indicating "in-phase" and left arrows indicating "anti-phase" relationships. It can be seen that a common region of high power exists with a nearly in-phase relationship between $\overline{SS}$ and precession at the period of 22 kyr.

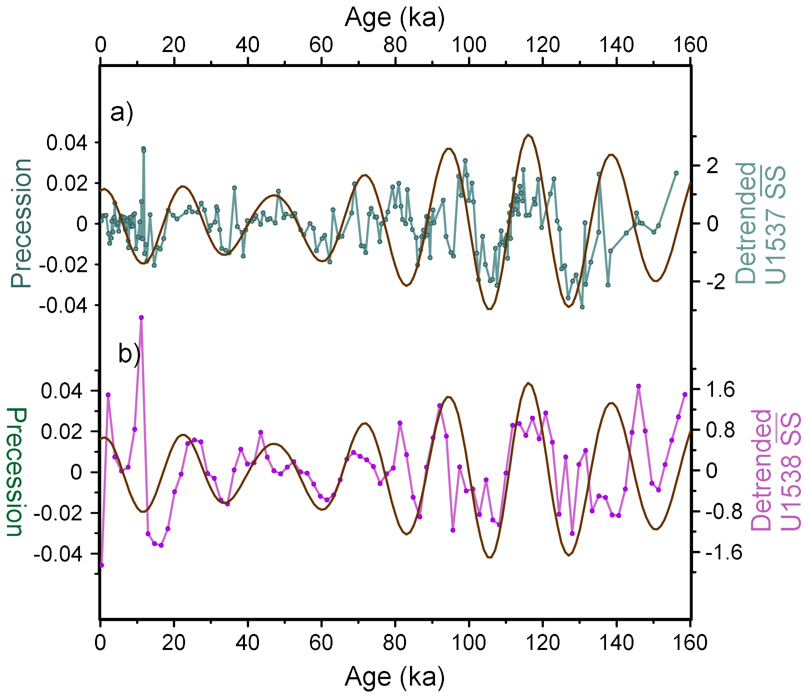

Fig. r4 | Comparison of detrended $\overline{SS}$ at Site U1537 and U1538 with precession index.

11. The Line 312-315 and Figure 4b: Actually, the alignment between U1537 and U1361 seems to break during the Holocene: is this the "decoupling" mentioned before?

Response:

Thank you for pointing out this important issue. Yes, the apparent misalignment between the U1537 and U1361 records[16] during the Holocene in Figure 4b does indeed reflect the "decoupling" phenomenon as we mentioned before. This decoupling possibly resulted from regionally heterogeneous responses of the Antarctic Ice Sheet to forcings such as oceanic warming or circulation shifts, such as the reinvigoration of the Atlantic Meridional Overturning Circulation and the subsequent increase in the intrusion of Circumpolar Deep Water[17], leading to divergent signals at these sites. We have expanded the discussion accordingly in the revised manuscript. Please see lines 346-351 in Main Text.

Other minor details:

1. Figure 1: Please add the numbers of the cores together with the names, i.e. (1) TPC063, 3956 m, (2) TPC077, 3774 m, and so on. As there's 13 of them, this will greatly facilitate their identification.

Response:

Thank you for your thoughtful suggestion. We have now added the core numbers along with the names in Figure 1 to make their identification easier. Please see lines 835-839 in Main Text.

2. Line 42: Please add "a" in "playing a key role".

Response:

Thank you for pointing that out. We have added "a" in "playing a key role" as suggested. Please see line 42 in Main Text.

3. Line 98: Please change "Dronning" to "Dome" (EDC stands for EPICA Dome C).

Response:

We have corrected this by changing "Dronning" to "Dome" as suggested. Please see line 97 in Main Text.

4. Line 103: Instead of 'sampling increments' in m (and sedimentation rates in cm/ka), it would be more straightforward to talk about sampling resolution in age.

Response:

We thank the reviewer for the constructive suggestion. We have revised the manuscript to replace "sampling increments in m" and "sedimentation rates in cm/kyr" with "sampling resolution in age" to provide a clearer and more straightforward description. Please see lines 99-100 in the Main Text.

5. Is Supplementary Figure 4 cited before Supplementary Figure 5?

Response:

Thank you for pointing that out. The citation order has been corrected, with Supplementary Figure 4 now cited before Supplementary Figure 5.

6. Line 118: Please change 'has' for 'have'

Response:

Thank you for your suggestion. We have changed "has" to "have" as requested. Please see line 115 in the Main Text.

7. Line 121: "ACC flow speeds can achieve flow speeds" – please remove one of the flow speeds.

Response:

Done. Thank you for your suggestion. Please see line 118 in the Main Text.

8. Line 128: Please change 'observation' to 'observations'

Response:

Thank you for pointing that out. We have revised "observation" to "observations." Please see line 119 in the Main Text.

9. Line 147: Please change 'Views' by 'View'

Response:

We have changed "Views" to "View" as requested. Please see line 143 in the Main Text.

10. Line 165: With the 'temporal pattern', you mean the temporal changes between the two cores? With the addition of the lines before, this sentence now needs to be rephrased.

Response:

We sincerely thank the reviewer for pointing this out. The term "temporal pattern" refers to the temporal changes in ACC records across different sites, including U1537, U1538, and other stations such as PS97/093-2. We have rephrased the sentence to ensure clarity. The revised sentence now reads: "Although the temporal pattern of ACC is consistent across different locations, such as U1537, U1538, and PS97/093-2, the intensity of ACC was likely distinct at different sites, for example, $\overline{SS}_{U1537}$ (14.1- 23.6 μm), $\overline{SS}_{U1538}$ (14.9- 25.7 μm), and other stations shown in Fig. 3, according to the range of mean value of grain size.". Please see lines 165-168 in Main Text.

11. Line 171: exhibits stable what? Please rephrase.

Response:

Thank you for your careful review. We have rephrased the sentence to clarify the meaning. The revised sentence is: "The $\overline{SS}$ record at Site U1537 located south of SACCF is relatively low during the Penultimate Glacial Maximum (PGM, 158-135 ka), with an average $\overline{SS}$ of 16.3±1.2 μm". Please see lines 171-173 in Main Text.

12. Line 624: Please change 'tracer' to 'tracers'.

Response:

Done.

13. Line 719: Please remove 'below'.

Response:

Done.

Reviewer #3 (Comments to Author (shown to authors):

1. After reviewing the changes made by the authors in response to comments, I feel that my concerns have been adequately addressed. The manuscript has been significantly improved in response to my and the other reviewer's comments. I feel that it is ready for publication and will serve as an important contribution to the field.

Response:

Thank you very much for the supportive comments. We are glad that the revisions have addressed your concerns, and we appreciate your recognition that the manuscript is now ready for publication.

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Point-by-point response to reviewers' comments

Reviewer #1 (Comments to Author (shown to authors):

1. The manuscript has again significantly improved and I thank the authors for their efforts. I still have some minor and technical comments, but overall I think the manuscript is now sufficiently clear and nearly ready for publucation.

Response:

We sincerely appreciate the reviewer's positive feedback and constructive suggestions. We have carefully addressed all comments and believe the current version meets the high publication standards of Nature Communications.

Minor comments:

2. Line 329: The period 70-80ka is mentioned as being different from the mechanism described above, but isn't the period before ~130ka also different?

Response:

We thank the reviewer for this insightful observation. The $\overline{SS}$ records during both the pre-~130ka and 70-80ka intervals deviate slightly from the orbital forcing (eccentricity and precession). By comparing these periods with Antarctic ice core temperature reconstructions, we identified consistent co-variation between $\overline{SS}$ and temperature, suggesting temperature forcing may have modulated $\overline{SS}$ variability. The specific mechanisms require further investigation. This clarification has been added to lines 338-343.

3. Line 339: How does this study suggest a link between ACC shifts and tropical climate variability? Please clarify in the text what you are refering to.

Response:

We appreciate the reviewer's request for clarification. The revised text now explicitly states that the coherent precessional patterns among ACC proxy records and tropical hydroclimate reconstructions suggest a potential linkage between orbital-scale ACC front shifts and tropical climate variability. Please see lines 348-351 for the updated explanation.

4. Line 359: how consistent is the $\overline{SS}$ record at U1537 really with the $\delta^{15}N_{db}$ and CO2 offset record (figure 4e)? Can you provide some type of quantification of this consistency?

Response:

We thank the reviewer for this valuable suggestion. To quantify the consistency, we calculated Pearson correlation coefficients between the U1537 $\overline{SS}$ record and the $\delta^{15}N_{db}$ and CO_2 offset records. The results (now presented in Fig. r1 and Supplementary Fig. 19) show a positive correlation with CO_2 offset (r= 0.56, n=149, P< 0.01) and a negative correlation with $\delta^{15}N_{db}$ offset (r=–0.47, n=149, P< 0.01). We have incorporated this analysis, associated explanation, and figure in this revised manuscript. Please see lines 370-378 in Main Text and Supplementary Fig. 19.

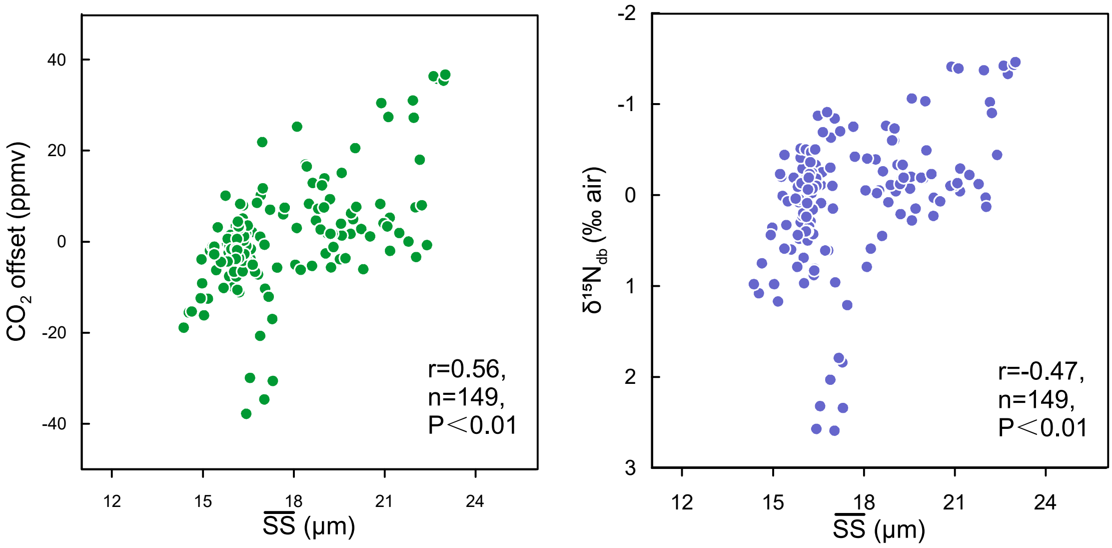

Fig. r1 (new Supplementary Fig. 19 of the revised manuscript) | Comparison between U1537 $\overline{SS}$ record and the CO_2[1] and $\delta^{15}N_{db}$ offset records[2]. Pearson correlation coefficients are r = 0.56 and r = –0.47, respectively.

5. Figure 2: I think it is worthwhile to note somewhere in the manuscript that the inferred ACC shifts do not fully align in time with the LIG. As is clear from figure 2 and mentioned in the text, the high $\overline{SS}$ values are found around 120-113ka, while the peak interglacial temperatures are generally considered to have occurred before 125ka and the temperature plateau in figure 4a would be ~127-118ka. Perhaps this is consistent with a dominant orbital forcing over the imprint of the glacial-interglacial cycle?

Response:

We appreciate this insightful comment. The revised manuscript now highlights that the peak ACC shifts occur at approximately 120-113 ka, while peak interglacial temperatures generally appear earlier, at ~128-118 ka, underscoring the distinct hydrological behavior of the ACC, and the dominance of orbital forcing over glacial-interglacial cycles. See lines 173-176 and 300-305.

6. Figure 3i: the figure would be visually even more convincing if the two 'data points' towards the northern part of this transect would not be given in terms of relative changes in their native interpretation (STF shifts in GeoB-3603-2 and temperature changes in PS75/034-2) but in terms of their implied changes in ACC position. In that way they would show negative relative changes while all data south of that would show positive relative changes (assuming that MD00-2375G would also be negative speed changes in contrast to what is shown now). Perhaps the authors regard such a figure as too much interpretation and too little raw data.

Response:

We are grateful for the reviewer's suggestion regarding Figure 3i. To enhance the visual representation of the southward displacement of ACC fronts, we revised Figure 3i by plotting northern sites (GeoB-3603-2 and PS75/034-2) below the horizontal reference line (y=0) with "ACC weakening" labels, while southern sites remain above it with "ACC strengthening" indicators (Fig. r2). This adjustment enhances visual coherence while preserving data integrity. Please see Figure 3i in Main Text.

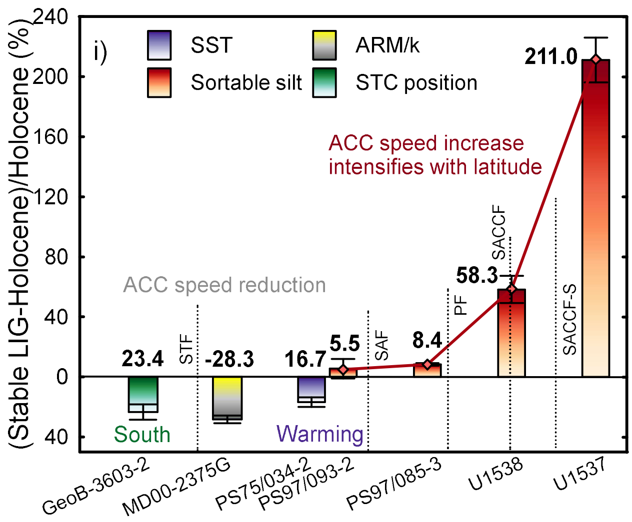

Fig. r2 (new Fig. 3i of the revised manuscript) | Comparison of current speed[3,4,5], sea surface temperature[6], and other proxies across the front during the LIG. The plotted values represent absolute values of the relative percent change between Stable LIG and Holocene, with error bars showing the estimated uncertainty of the relative difference.

Technical comments:

1. Line 57: "~45°S and"

Response:

Thank you for pointing this out. We have revised accordingly. Please see line 55 in Main Text.

2. Line 62: Comma after "fronts"?

Response:

Added as suggested. Please see line 60 in Main Text.

3. Line 66: "changes in the ACC's position"?

Response:

We have revised as suggested. Please see line 66 in Main Text.

4. Line 81: “topografic constraint”?

Response:

Corrected as suggested. Please see line 80.

5. Line 116: Does the reader know what SS% or SSFS% are?

Response:

We have provided more explanation for what SS% or SSFS% are as suggested. Now the sentence is “Strong correlation between $\overline{SS}$ and SS% (percentage of sortable silt), as well as between $\overline{SSFS}$ and SSFS% (percentage of sortable silt plus fine sand) indicate that the sediments have undergone current-sorting”. Please see lines 115-117 in Main Text.

6. Line 211: SAF is SAF-S in figure 3h?

Response:

Yes, SAF in the text corresponds to SAF-S in Figure 3h. We have revised the manuscript to use consistent terminology. Please see lines 208-210 in Main Text.

7. Line 234: Don’t start the new paragraph with ‘whereas’

Response:

We have revised the sentence to avoid starting the paragraph with “whereas” as suggested. Please see line 233 in Main Text.

8. Line 251: Remind the reader to which core, data and/or figure you are refering to when speaking about the current speeds at Drake Passage.

Response:

Thank you for your helpful suggestion. We have added references to the cores (Sites PS97/093-2 and PS97/085-3) and Figure 3i in the text in this revised manuscript. Please see lines 249-252 and Figure 3i in Main Text.

9. Line 262: shouldn't the value of the relative change in flow speeds of MD00-2375G be negative in figure 3i?

Response:

Thank you very much for your careful checking. Yes, the value for MD00-2375G in Figure 3i should be negative. In Figure 3i, we used absolute values to highlight magnitude, and plotted sites indicating ACC weakening (including MD00-2375G) below the horizontal reference line (y = 0) to reflect the direction of change. Please see Figure 3i.

10. Line 264: clarify which core and/or data point in figure 3i you are refering to with 'Cape Basin'.

Response:

We have clarified the reference to the Cape Basin by explicitly indicating the core site (Site GeoB3603-2) in this revised manuscript as suggested. Please see line 266 in Main Text.

11. Lines 320-323: Don't you already discuss the detrended $\overline{SS}$ data from sites U1537 and U1538 above? So you cannot introduce it here as 'further evidence' for you line of reasoning?

Response:

Thank you very much for your careful reading and valuable comment. We agree that the detrended $\overline{SS}$ data from Sites U1537 and U1538 were discussed earlier in the manuscript. Accordingly, we have revised the relevant section to clarify that the consistent precessional variability observed among these $\overline{SS}$ records, the Southern Hemisphere westerlies reconstructions, and Intertropical Convergence Zone records collectively reinforce our interpretation, rather than introducing the $\overline{SS}$ data as entirely new evidence. Please see lines 327-330 in Main Text.

Reviewer #2 (Comments to Author (shown to authors):

1. I thank the authors for the substantial effort they have done in answering my and the other reviewers' previous comments, I feel that the manuscript has greatly evolved and shifted its focus towards a more clear message. It is now very much improved and ready for publicatio

Response:

Thank you very much for the supportive comments. We are glad that the revisions have addressed your concerns, and we appreciate your recognition that the manuscript is now ready for publication.

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